

True substrates: The exceptional resolution and unexceptional preservation of deep time snapshots on bedding surfaces

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Associate Editor – Eric Hiatt

ABSTRACT

Rock outcrops of the sedimentary–stratigraphic record often reveal bedding planes that can be considered to be true substrates: preserved surfaces that demonstrably existed at the sediment–water or sediment–air interface at the time of deposition. These surfaces have high value as repositories of palaeoenvironmental information, revealing fossilized snapshots of micro-scale topography from deep time. Some true substrates are notable for their sedimentary, palaeontological and ichnological signatures that provide windows into key intervals of Earth history, but countless others occur routinely throughout the sedimentary–stratigraphic record. They frequently reveal patterns that are strikingly familiar from modern sedimentary environments, such as ripple marks, animal trackways, raindrop impressions or mudcracks: all phenomena that are apparently ephemeral in modern settings, and which form on recognizably human timescales. This paper sets out to explain why these short-term, transient, small-scale features are counter-intuitively abundant within a 3.8 billion year-long sedimentary–stratigraphic record that is known to be inherently time-incomplete. True substrates are fundamentally related to a state of stasis in ancient sedimentation systems, and distinguishable from other types of bedding surfaces that formed from a dominance of states of deposition or erosion. Stasis is shown to play a key role in both their formation and preservation, rendering them faithful and valuable archives of palaeoenvironmental and temporal information. Further, the intersection between the time–length scale of their formative processes and outcrop expressions can be used to explain why they are so frequently encountered in outcrop investigations. Explaining true substrates as inevitable and unexceptional by-products of the accrual of the sedimentary–stratigraphic record should shift perspectives on what can be understood about Earth history from field studies of the sedimentary–stratigraphic record. They should be recognized as providing high-definition information about the mundane day to day operation of ancient environments, and critically assuage the argument that the incomplete sedimentary–stratigraphic record is unrepresentative of the geological past.

Keywords Bedding planes, sedimentary stasis, sedimentary structures, stratigraphic time, taphonomy.

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BEDDING SURFACES

Bedding surfaces are innate components of sedimentary strata, and essential to their geological understanding. Practically, they can be traced, quantified and interpreted, in order to demarcate the hierarchy of building blocks which constitute the sedimentary–stratigraphic record (SSR; e.g. Allen, 1983; Miall, 2010). Conceptually, they are recognized as hiatuses or gaps of missing time that are endemic to this record (e.g. Barrell, 1917; Ager, 1981, 1993; Dott, 1983; Miall, 2016a) and which can present challenges for interrogating the order of ancient events and processes, and the rates at which they happened (e.g. Ager, 1981, 1993; Torrens, 2002; Erwin, 2006; Jerolmack & Paola, 2010; Kemp, 2012; Kemp *et al.*, 2015; Miall, 2015; Trabucchi-Alexandre, 2015; Holland, 2016; Tipper, 2016; Saraswati, 2019).

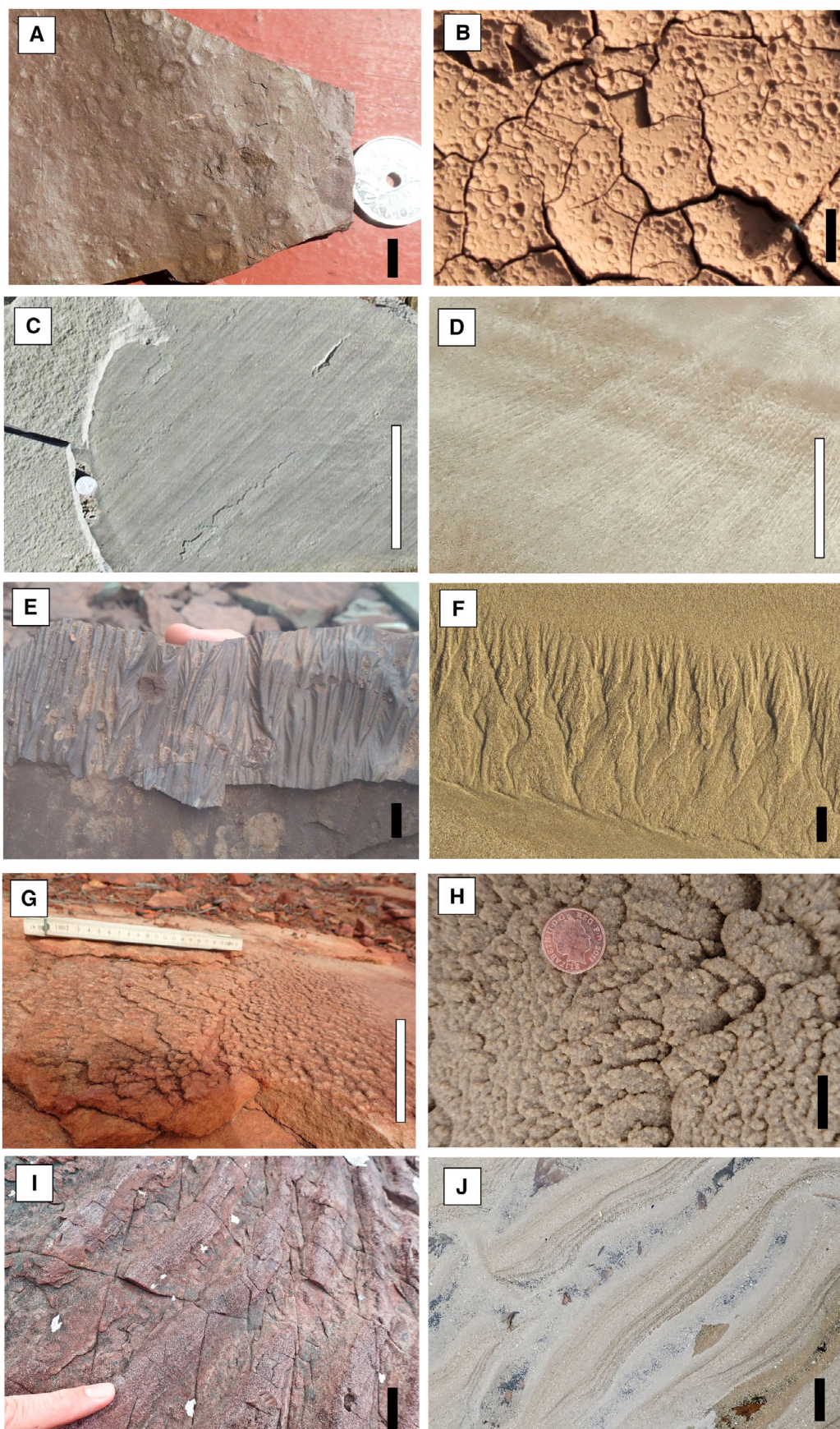
The relative temporal vacuity of bedding surfaces has been suggested to limit the fidelity of the SSR as a historical chronicle (e.g. Ager, 1993). Yet, at outcrop, many present the observer with an apparent paradox, in that the incomplete record archives apparently transient topographies and signatures of ancient substrates in extraordinarily high-resolution detail. Physical structures such as ripple marks, raindrop impressions or mudcracks (Fig. 1), and signatures of biological activity including animal trackways, burrow openings and even stranded jellyfish (Fig. 2) are peppered throughout the global SSR, meaning that many ancient bedding surfaces have a direct and striking comparability to modern-day substrate patterns that could be witnessed momentarily on a beach or dry riverbed.

These abundant but enigmatic ‘true substrates’ (‘sedimentary bedding planes that demonstrably existed at the sediment–water or sediment–air interface at the time of deposition, as evidenced

by features such as ripple marks or trace fossils’: Davies & Shillito, 2018) pose profound questions related to the reading of the SSR as an historical chronicle, and the interpretation of ancient life and environments. How is it possible that a 3.8 Ga long sedimentary record, that may be up to 90% incomplete [at 10^6 timescales; Miall (2016a,b)], so consistently stores geological ephemera that instinctively have negligible preservation potential? Further, when they are encountered, can they be trusted as reliable repositories of palaeoenvironmental information? Examples from key intervals of Earth history are known to provide high-definition glimpses of Ediacaran sea-beds populated with early metazoans (e.g. Mitchell *et al.*, 2020), Devonian forest floors during the greening of the continents (e.g. Stein *et al.*, 2020), sharply defined trackways of Mesozoic dinosaurs (e.g. Shillito & Davies, 2019a) and late Cenozoic footprints of ancestral humans (e.g. Ashton *et al.*, 2014). These cases (and many less prominent examples) are frequently considered to be windows into the past that can archive profound insights into ancient Earth, but pose a question as to whether they are characteristic samplings. Or, instead, are they freak accidents that escaped destruction through exceptional circumstances, rendering them unrepresentative anomalies amongst a recycled and lost norm?

This paper contributes new insights to address aspects of these persistent questions, from the perspective of sedimentary geological field observations and theory. It builds upon a recent surge in understanding pertaining to the time-significance of sedimentary strata, developed from modelling approaches (e.g. Ganti *et al.*, 2013, 2020; Reesink *et al.* 2015; Sadler & Jerolmack, 2015; Tipper, 2015; Straub & Foreman, 2018; Straub *et al.*, 2020) and new theoretical frameworks (e.g. Miall, 2015; Paola *et al.*, 2018; Holbrook & Miall, 2020). These key ideas are

Fig. 1. Examples of physical sedimentary structures providing evidence for true substrates in the SSR (on the left), with modern analogues (on the right). (A) and (B) Raindrop impressions. (A) Silurian Sundvollen Formation, Kroksund, Norway. (B) Boom River, Kyrgyzstan. (C) and (D) Parting lineation developed in plane bed flow regime. (C) Devonian Escuminac Formation, Miguasha, Quebec, Canada. (D) Alnmouth, Northumberland, England. (E) and (F) Rill marks formed by draining water. (E) Mississippian Shepody Formation, Peck’s Point, New Brunswick, Canada (hyporelief cast of true substrate). (F) Holkham, Norfolk, England. (G) and (H) Adhesion ripples (see Kocurek & Fielder, 1982). (G) Silurian Tumblagooda Sandstone, Kalbarri, Western Australia. (H) Holkham, Norfolk, England. (I) and (J) Water-level drainage marks on ripple flanks. (I) Mesoproterozoic Meall Dearg Formation, Rubha Réidh, Scotland. (J) Alnmouth, Northumberland, England. White scale bars are 10 cm long; black scale bars are 1 cm long.



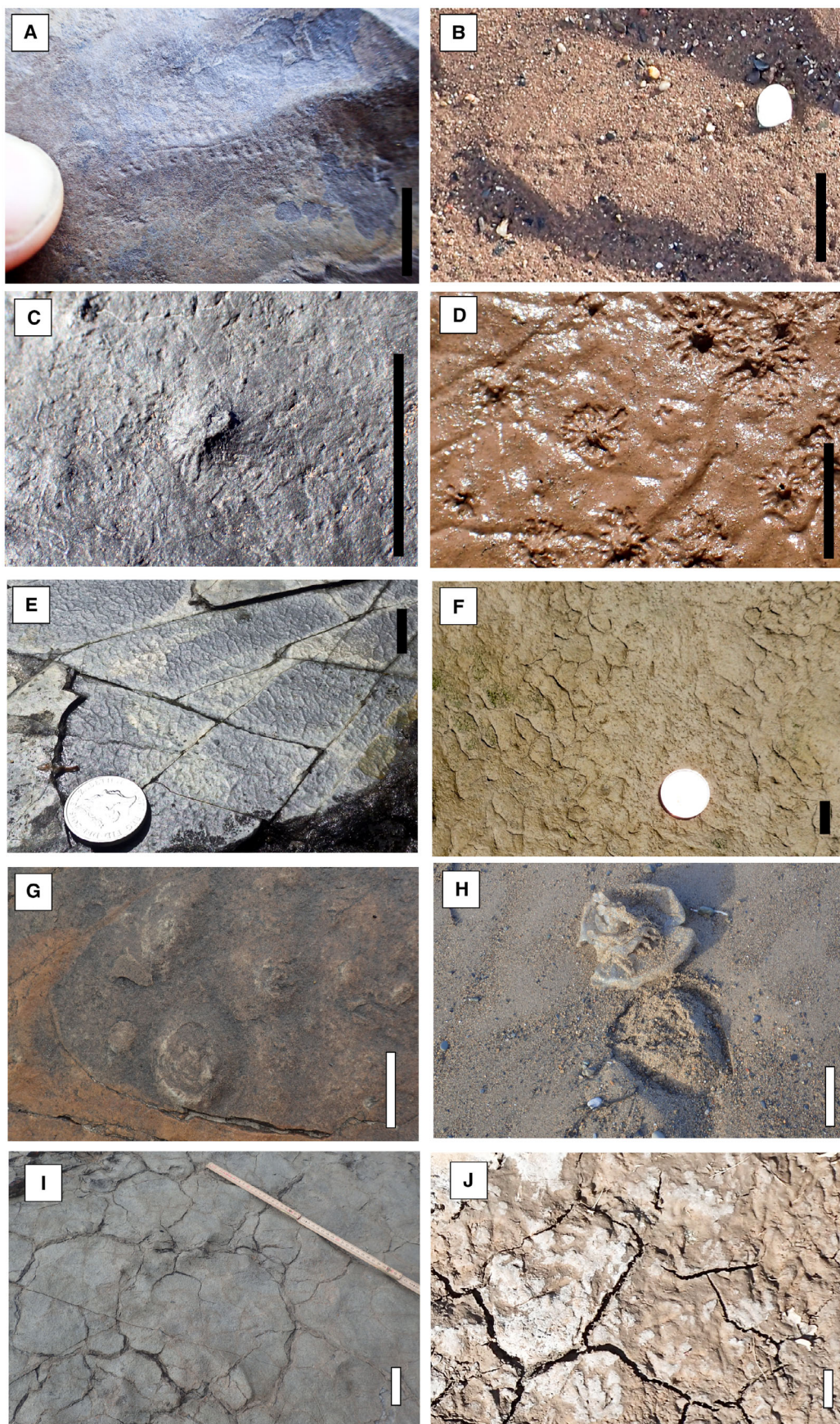


Fig. 2. Examples of biological sedimentary structures providing evidence for true substrates in the SSR (on the left), with modern analogues (on the right). (A) and (B) Arthropod trackways crossing ripple mark crests. (A) Silurian Sundvollen Formation, Kroksund, Norway. (B) Rainy Cove, Nova Scotia, Canada. (C) and (D) Stellate form to aperture of vertical invertebrate feeding burrows. (C) Mississippian Horton Bluff Formation, Blue Beach, Nova Scotia, Canada (hyporelief cast of true substrate). (D) Hopewell Rocks, New Brunswick, Canada. (E) and (F) Reticulate marking due to tangling of biological filaments. (E) Neoproterozoic Diabaig Formation, Diabaig, Scotland. (F) Rye, Sussex, England. (G) and (H) Sand-filled impressions of stranded jellyfish. (G) Cambrian Potsdam Sandstone, Rainbow Falls, New York, USA. (H) St. Cyrus, Scotland. (I) and (J) Desiccated and dried-out microbial mat. (I) Pennsylvanian Parrsboro Formation, West Bay, Nova Scotia, Canada. (J) Stiffkey, Norfolk, England. White scale bars are 10 cm long; black scale bars are 1 cm long.

here developed and translated so that they have applicability for interpreting true substrates and other bedding surfaces when they are encountered in the field. In doing so, the aim is to shed light on the often counter-intuitive taphonomic pathways of true substrates, and potential roots of interpretive bias that can arise due to the time–length scale recorded by natural rock outcrops.

To achieve these aims, a catalogue of true substrates within siliciclastic strata, from across the geological timescale, is presented. First, true substrates are considered amongst a plethora of other types of bedding surface, to identify what makes them particular, and then practical approaches to their study are discussed. Accordingly, this paper is divided into six sections: (i) *Construction* – a summary of theoretical considerations about how bedding surfaces are created; (ii) *Classification* – an explanation of how bedding surfaces can be practically classified, and which constitute true substrates; (iii) *Identification and Interpretation* – a discussion of the palaeoenvironmental and temporal significance of the surface characteristics of true substrates; (iv) *Preservation* – a discussion of the conditions under which true substrates can resist erosional shear stresses, aiding their long-term preservation; (v) *Observation* – where factors that promote or hinder the possibility to observe true substrates at the present day are highlighted; and (vi) *Implications* – a summary of how recognizing the existence and abundance of true substrates can influence the reading of the SSR as an archive of Earth history.

Note on terminology

Published terminology used to describe stratal surfaces can vary, so clarification and justification for terminology used in this study is given here. Campbell (1967) and Reineck & Singh (1980) are followed in the use of the term *bed* to

refer to a thickness-independent genetic unit comprising a coherent layer of sedimentary rock, or sediment, bounded above and below by bedding surfaces, and *laminae* to refer to ‘small beds’ that constitute the smallest (visible) layers of a hierarchical succession, internal to beds. This definition deviates from the scale-based definition, where beds are >1 cm thick and laminae are <1 cm thick (McKee & Weir, 1953), that is frequently adopted in textbooks (e.g. Miall, 2016b; Collinson & Mountney, 2019). Both definitions have merit depending on the focus of study, but Campbell’s (1967) definition enables the discussion of general concepts that apply irrespective of bed/lamina thickness, but which still require hierarchical phenomena to be differentiated.

The term *bedding surface* is used in a restricted sense to that of Campbell (1967), to refer to bounding surfaces, within conformable successions, which acted as the depositional surface for overlying sediment: the potential variety of origins of which are a major focus throughout this paper. It will become practically necessary to distinguish different expressions of bedding surfaces in natural rock outcrops. For this reason, bedding surfaces that present as cross-sections (for example, in a vertical cliff face of horizontal strata) are referred to as *bedding contacts* (*sensu* Allen, 1983) and the term *bedding plane* is reserved to refer specifically to instances where spatially extensive plan-views of bedding surfaces are accessible.

The bedding surfaces discussed here are restricted to examples from siliciclastic settings (unless otherwise stated), and a modification of these concepts may be required to make them applicable to carbonate settings. Most examples come from littoral and non-marine settings, due to the present authors’ research interests and the accessibility of modern analogues, but the generalities discussed also apply to deep marine settings, where similar processes are increasingly

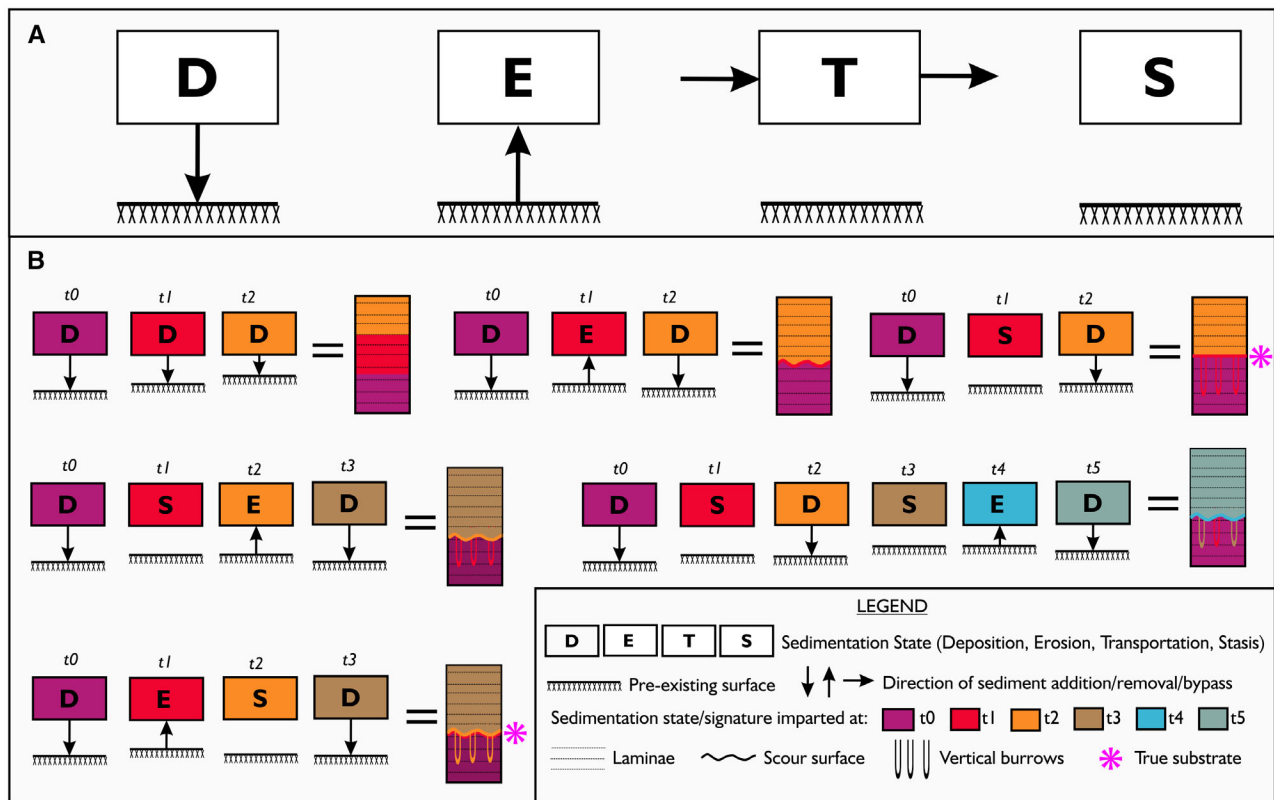


Fig. 3. Sedimentation states and the accrual of stratigraphic signatures. (A) Simplified illustration of different states in an active sedimentary system: deposition (D), erosion (E), stasis (S) and transportation (T; after Tipper, 2015). (B) Illustration of how state changes at a local site over time may lead to bedding surfaces which testify to these compound sedimentation states. For illustrative purposes 'E' is shown associated with an irregular bedding surface and 'S' is associated with emplacement of a vertical burrow fabric.

recognized to be in operation (Trabucho-Alexandre, 2015; Schieber, 2016).

CONSTRUCTION: DEPOSITION, TRANSPORT, EROSION AND STASIS

Bedding surfaces record changes in depositional conditions that have terminated the preserved record of sedimentation of an antecedent bed, either through erosional truncation or a shift in flow or sediment regime. Such changes are commonly referred to as 'abrupt' (e.g. Campbell, 1967; Patzkowsky & Holland, 2012), but this term should be understood in the material sense of being a terminal stratal break as it carries no temporal implication of suddenness, nor scale implication of the catastrophic (Dott, 1983). They are inevitable components of stratal packages that accrue in sedimentation systems because sedimentation states (*sensu* Tipper, 2015) are in flux over time.

Sedimentation states

Tipper (2015) highlighted how recognizing that there are four sedimentation states can refine understanding of the construction of the SSR. These states are deposition (D), erosion (E), transportation (T) and stasis (S; Fig. 3A). Of these, only D, E and S are directly relevant to interpreting the SSR (Tipper, 2015), because a T state, while important for understanding active sedimentary environments, cannot leave a physical record without being coupled with one of the other states (D + T, E + T or S + T). When considering the accrual of an idealized one-dimensional vertical stratigraphic column, the states have different effects on the lithic surface of a sedimentary pile: D lays down sediment, elevating the surface; E takes up sediment, producing a negative change to the surface; and S involves neither deposition nor erosion, leading to no change in the elevation of the surface. In this way of perceiving the stratigraphic record,

any iteration of the lithic surface that ends up becoming locked into a stratigraphic column is a bedding surface.

Tipper's (2015) championing of the importance of stasis has been influential (e.g. Hajek & Straub, 2017; Paola *et al.*, 2018; Straub & Foreman, 2018; Straub *et al.*, 2020), and further modelling has supported the contention that it has been inevitable and the dominant state throughout the historic accrual of the SSR. Straub *et al.* (2020) reasoned that because, at the smallest scale, the sedimentary record is built by flashes of deposition where sedimentary particles arrive instantaneously, sedimentation rates are infinite at the time of grain arrival and this must be balanced by long intervals of stasis. Stasis has also been shown to be particularly important within shorter term processes, typical of those which create lower order bounding surfaces (Straub & Foreman, 2018), and within less mobile parts of an active sedimentary environment, which are likely to dominate spatially when erosion and deposition are strongly focussed in a particular subenvironment (Hajek & Straub, 2017; Straub *et al.*, 2020).

Evidence for sedimentation states in natural rock outcrops

In addition to having importance for stratigraphic models, different sedimentation states are useful to consider in geological field investigations. Outcrops of strata yield not only evidence of deposition (i.e. beds) and erosion (for example, scour surfaces), but also many stasis signatures (for example, Figs 1 and 2) that could only have been registered during intervals when no significant deposition or erosion was happening, and which are crucial for the recognition of true substrates (e.g. Davies *et al.*, 2017; Davies & Shillito, 2018; McMahon *et al.*, 2020). To translate recent theoretical understanding for practical application to the fuzzy realm of real-world rock outcrops, a few clarifications are first required concerning: (i) the spatiotemporal area that can be affected by a sedimentation state; (ii) the gradational boundaries between D, E and S that emerge when considering them at a lower resolution; and (iii) the potential for the accrual of information during stasis.

Many advances from the realm of numerical stratigraphy rely on understanding changes in sedimentation state at Euclidean points (e.g. Crowley, 1984; Tipper, 2015). This permits D, E and S to be considered as perfect states in models but has limited practical application to

interpretations of geological outcrops, where observed phenomena have both spatial locations and magnitude. Accordingly, when sedimentation states are referred to in this paper, it is in reference to the net state that has affected the field of view, i.e. a particular spatial patch of interest such as a bedding plane (or part thereof).

This broadening of the frame of interest blurs the boundaries between D, E and S, and their interpretation unavoidably becomes slightly more subjective. For example, is a patch of sandy substrate on which no net deposition is occurring, but over which a train of ripples is migrating, in a state of S, or in a continual flux between D and E? At any Euclidean point, the latter is clearly the case. However, the former has more practical application in geological observations: thus, here, the sedimentation state is considered to be that which dominated over the time-length scale on which the patch of interest operated before it was fully interred. In many instances this definition of stasis encapsulates the 'surface active layer' (Wheatcroft *et al.*, 2007); that part of the substrate that can be mobile despite no net deposition (for example, extending from the crest to the base of ripple troughs).

Tipper (2015) stated that, because stasis is a state of neither deposition nor erosion: "nothing is happening in the system that needs to be recorded ... hence nothing is recorded!". This perspective considers only the addition or removal of sediment. In practice, surfaces in net stasis can continue to register structures and information, which can themselves be indirect signatures of the passage of time (Paola *et al.*, 2018). As it is significant that observable signatures (for example, sedimentary structures, geochemical profiles or trace fossils) can accrue during stasis, it is essential to differentiate between additive, reductive and neutral effects on a sediment pile, versus constructive, destructive and neutral impacts on sedimentary signatures (Table 1).

The role of compound sedimentation states in the formation of bedding surfaces

As, by definition, bedding surfaces record discontinuity in deposition, their formation must rely on changes between, or in the intensity of, sedimentation states. This means that they can be categorized by the compound sequence of sedimentation states that led to their formation

Table 1. Sedimentary system states and combinations of sedimentary system states that may affect a particular spatial cell of an active sedimentary environment at any given instant of time.

State	Effect on sediment pile	Effect on sedimentary signatures
D (\pm T)	Additive	Constructive
E (\pm T)	Reductive	Destructive
S (\pm T)	Neutral	Neutral, Constructive or Destructive

(Fig. 3). Such compound states must always be bookended by D (because any bedding surface must be sandwiched between deposited beds), but there may be geological evidence to identify the order of states that passed between D¹ and D². The most common types of surface that it may be possible to identify are D–D–D surfaces, D–E–D surfaces, D–S–E–D surfaces, D–S–D surfaces and D–E–S–D surfaces, the latter two of which can preserve true substrates (Fig. 3). Whenever a compound state includes E, there may be under-determination of complexity, because of the potential for the E component to have erased multiple once-existent records of antecedent sedimentation states (e.g. Straub & Foreman, 2018). Accordingly, more complex surfaces likely exist in greater numbers than can ever be positively diagnosed, and D–S–E–D surfaces are probably near the upper limit of most commonly achievable resolution: identifiable where downward-penetrative signatures were imparted during stasis (for example, vertical burrows, palaeosol profiles) and later only partially truncated by erosion. However, fortuitous preservation may extend the range of identifiable surfaces in some instances: Fig. 3 highlights the identification of a D–S–D–S–E–D surface where two distinct generations of deeply penetrative vertical burrows have been registered at different lithic surfaces of successive, vertically juxtaposed beds, and where a later erosive event has scoured down to a level internal to the lower bed. In such an instance, special criteria would be needed to prove that the truncated burrows were palimpsested – for example, Kotake (1994) was able to distinguish distinct synchronous populations of *Zoophycos* burrows, palimpsested within the same host bed, by virtue of some individuals containing tuffaceous pellets related to a volcanic ash event.

CLASSIFICATION OF BEDDING SURFACES

True substrates fall within a broader group of bedding surfaces that accurately record *synoptic topography*: true chronostratigraphic surfaces, which by necessity were also once geomorphic surfaces at the interface of sediment and water/air (Paola *et al.*, 2018). Specifically, they are instances of synoptic topography that yield preserved evidence for sedimentary stasis and crop out as bedding planes. To fully understand the significance of true substrates, it is first necessary to recognize how they relate to other types of bedding surface that do not match these criteria, but which may also be encountered during geological investigations. This section classifies and describes the full array of natural bedding surfaces to emphasise the particularity of true substrates, and a summary of the terminology used is presented in Fig. 4.

Classification of bedding contacts

Bedding contacts in vertical sections have long been differentiated by reference to the processes that formed them, but such interpretations have usually only considered deposition and erosion as sedimentation states (e.g. Allen, 1983). Ganti *et al.* (2013) usefully distinguished two types of bedding contacts within experimentally-produced sediment piles generated by migrating bedforms: (i) *sampled topography* – any bedding contact, or part of a bedding contact, that ever existed as a geomorphic surface during the evolution of the sediment pile (i.e. sampled synoptic topography); and (ii) *constructed topography* – visible surfaces preserved in the sediment profile that were an artefact of its evolution but which never existed as geomorphic surfaces. Examples of constructed topography could include truncation surfaces where bedforms, migrating at different rates, have merged (e.g. Myrow *et al.*, 2018), or the depositional down-dip amalgamation of bedform topsets to create an apparent planar surface (e.g. Gani, 2017).

Different lines of evidence can be used to distinguish these in vertical sections (Fig. 5) but the information that they host, and their confident diagnosis, can be limited by their two-dimensional expression. Identifying a true substrate with a compound sedimentation state of D–E–S–D (i.e. synoptic topography) can be reliant on surficial sedimentary structures that are not always apparent in a vertical section (e.g.

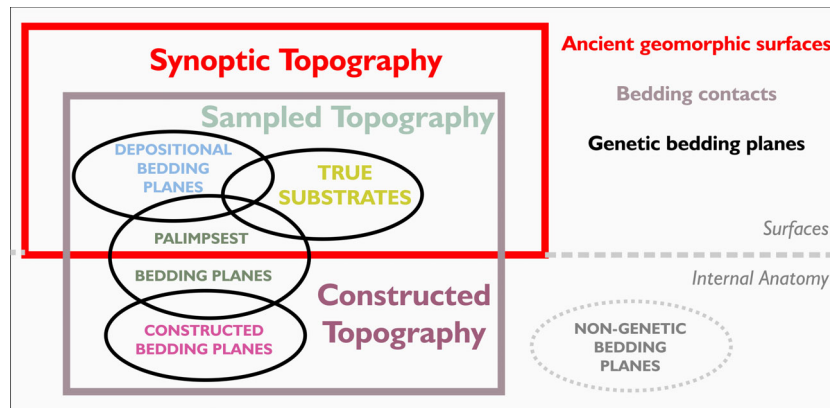


Fig. 4. Terminology used here, showing different classes of bedding surface. Gaps and overlap between the enclosed terms are intentional and signify the porous boundaries of the classes and issues of under-determination discussed in the text. Terms towards the top of the figure refer to surfaces that were once topographic contacts between the sediment surface and water/air. Terms towards the bottom of the figure refer to surfaces within the internal anatomy of the sediment pile.

Davies & Shillito, 2018; see *Classification of bedding planes*). In such instances, actual D–E–S–D surfaces (equivalent to sampled topography) may be misidentified as apparent D–E–D surfaces [equivalent to constructed topography, and generally perceived as being more common (e.g. Rubin & Hunter, 1982; Allen, 1983)]. Thus, while the differentiation of surfaces in vertical section can be informative (Fig. 5), it is essential to recognize the potential for under-determination and that bedding contacts can archive different information to bedding planes.

Classification of bedding planes

A liberal definition of bedding planes includes splits in strata that are parallel to bedding, but which are internal to homogenous beds, or a result of separation along planes of secondarily created material discontinuity (such as fissility, Macquaker & Adams, 2003; Trabucho-Alexandre, 2015). Such planes can have utility (for example, for determining tectonic strike and dip), but are of limited value for interpreting primary depositional conditions because they are neither sampled nor constructed topography. For holistic differentiation, these are referred to as *non-genetic bedding planes* and examples are highlighted in Fig. 6.

A converse grouping, *genetic bedding planes* which arise from primary depositional causes, can be classified based on the compound sedimentation states that created them. This is possible because the array of information stored in

plan-view (for example, Figs 1 and 2) often permits more refined and confident interpretations than is possible for vertical bedding contacts. Four types are discussed here: (i) constructed bedding planes (D–E–D and D–S–E–D surfaces); (ii) depositional bedding planes (D–D–D surfaces); (iii) true substrates (D–S–D and D–E–S–D surfaces); and (iv) palimpsest bedding planes.

Constructed bedding planes

Constructed bedding planes (Fig. 7) form due to compound sedimentation states of D–E–D or D–S–E–D, with negligible stasis having been involved between the erosional carving of the surface and deposition of the overlying bed. They are equivalent to constructed topography in vertical profiles and can be inferred where there is evidence that the bedding plane was created during an episode of near synchronous scour-and-fill, or where the bedding plane truncates sedimentary signatures internal to the underlying bed. However, given that instances of D–E–S–D are known to occur (see *Identifying and interpreting D–E–S–D true substrates*) and positive diagnosis of these may be precluded by an absence of fortuitous evidence, the apparent abundance of constructed bedding planes in the SSR may be an overestimate (cf. constructed topography). Nonetheless, confident identification is possible in some instances: for example, erosional sole marks with particularly steep, distorted or remnant overhanging margins can be used to imply that there was negligible time between scouring and casting, as they would

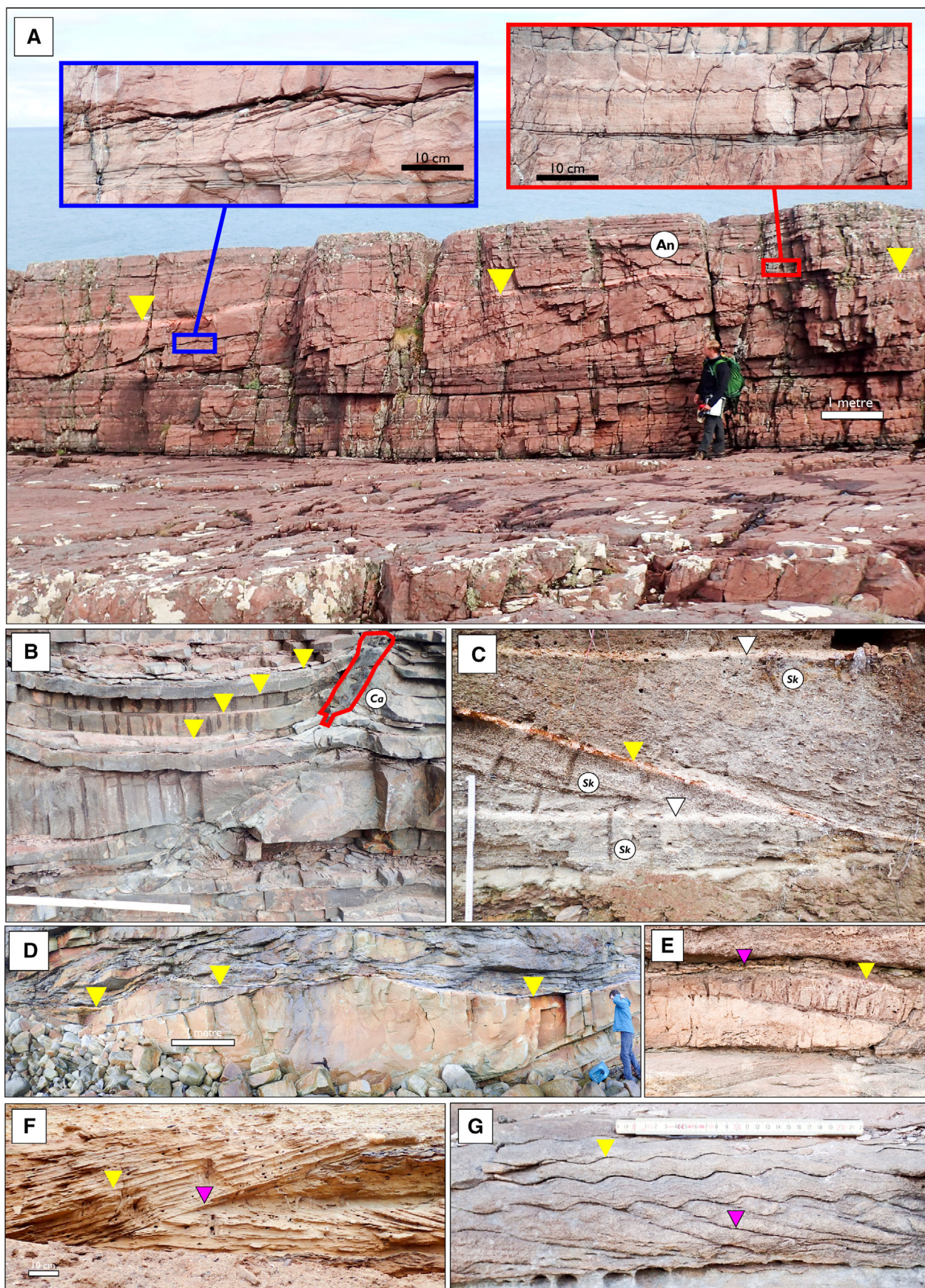


Fig. 5. Examples of bedding contacts in vertical section, recognized as sampled or constructed topography by cross-sections of original bedform surfaces or evidence for stasis. (A) Cliff preserving multiple instances of sampled topography, revealed by full relief preservation of bedforms, including convex-upward surface recording humpback dune form-sets (yellow arrows), convex-upward antidune bedforms (An) and cross-sections of rippled surfaces (red inset) and small dunes (blue inset). Strata were deposited during strongly aggradational conditions of high-energy river floods; Mesoproterozoic Meall Dearg Formation, Rubha Réidh, Scotland [see McMahon & Davies (2018a,b)]. (B) Sampled topography revealed by very fine-grained sandstones (yellow arrows) upturning as successive drapes around the base of a standing *Calamites* fossil (Ca); alluvial facies of the Pennsylvanian Tyne-mouth Creek Formation, McCoy Head, New Brunswick, Canada (visible part of metre-stick is 40 cm long). (C) Cross-strata foresets are sampled topography, potentially from a depositional instant: here they are revealed as having persisted as synoptic topography long enough to be colonized by *Skolithos* burrows – note how the burrows on the foresets are inclined, maintaining a perpendicular contact with the depositional surface, while fully vertical burrows descend from surfaces for which it is unclear whether they are constructed topography (with truncated burrows) or sampled topography (see Pollard *et al.*, 1993; Davies *et al.*, 2019). Subtidal facies of the Pliocene Red Crag Formation, Capel Green, Suffolk, England (visible part of metre-stick is 40 cm long). (D) Sampled topography of ridge-and-swale topography (yellow arrows) of a meandering river point bar; Middle Jurassic Scalby Formation, Yorkshire, England. (E) Convex-upward bedform and inclined vertical burrows show sampled topography with vertical burrow tops preserved (yellow arrow), passing along same bedding contact to become constructed topography with truncated burrow tops (pink arrow). Intertidal facies of the Ordovician Graafwater Formation, Carstenberg Pass, Western Cape, South Africa (visible part of metre-stick is 20 cm long). (F) Sampled topography of dune foresets (yellow) contrasting with erosional constructed topography formed by scour into pre-existing sediment pile; shallow subtidal facies of the Pliocene Red Crag Formation, Boyton Marshes, Suffolk, England. (G) Climbing ripples exhibit surfaces that are sampled topography of original rippled surface (for example, yellow arrow), while angle of climb has resulted in other prominent surfaces that cross time-lines (see Gani, 2017) and are constructed topography (for example, pink arrow); Silurian Tumblagooda Sandstone, Kalbarri National Park, Western Australia (visible part of metre-stick is 20 cm long).

otherwise have collapsed under the combined influences of ambient fluids and gravity (Myrow, 1992).

Depositional bedding planes

Depositional bedding planes (Fig. 8) form due to compound sedimentation states of D–D–D, where the intensity of deposition has fluctuated but never ceased. Again, confident differentiation may be hampered by under-determination from available evidence, but it can be possible to differentiate surfaces that developed during near-continuous sedimentation from those in which there were prolonged interludes of non-sedimentation. For example, certain trace fossils, such as vertical burrows, can be used to determine whether cross-strata record deposition by continually or intermittently mobile dunes. If observed burrows are fully vertical, with upper terminations on cross-bed topsets, it can be inferred that the environment of deposition hosted a viable population of burrowing organisms but that they were precluded from colonizing dune foresets (a case for D–D–D). In contrast, if the burrows are sub-vertically inclined, with upper terminations on individual foresets, it can be recognized that the burrowing organisms were not precluded from colonizing

the dune slipface (a case for D–S–D; for example, Fig. 5C; Pollard *et al.*, 1993; Davies *et al.*, 2019).

True substrates

True substrates form due to compound sedimentation states where the state immediately preceding the overlying bed was one of stasis (for example, D–S–D or D–E–S–D; Figs 9 and 10). As the chief focus of this paper, their identification and implications are discussed in detail in later sections.

Palimpsest bedding planes

Some palimpsesting is inevitable during the creation of true substrates: multiple generations of physical and biological signatures can be registered on the same ‘canvas’ during the interval that it persists as the lithic surface (Davies *et al.*, 2017). However, palimpsest bedding planes are considered to be those which either: (i) host signatures of states of D, E or S, that were demonstrably non-contemporaneous with the synoptic topography of the bedding plane of interest, extending from above or below beds; or (ii) are completely overprinted with signatures of states of D, E or S that developed after the active lithic surface had migrated above the

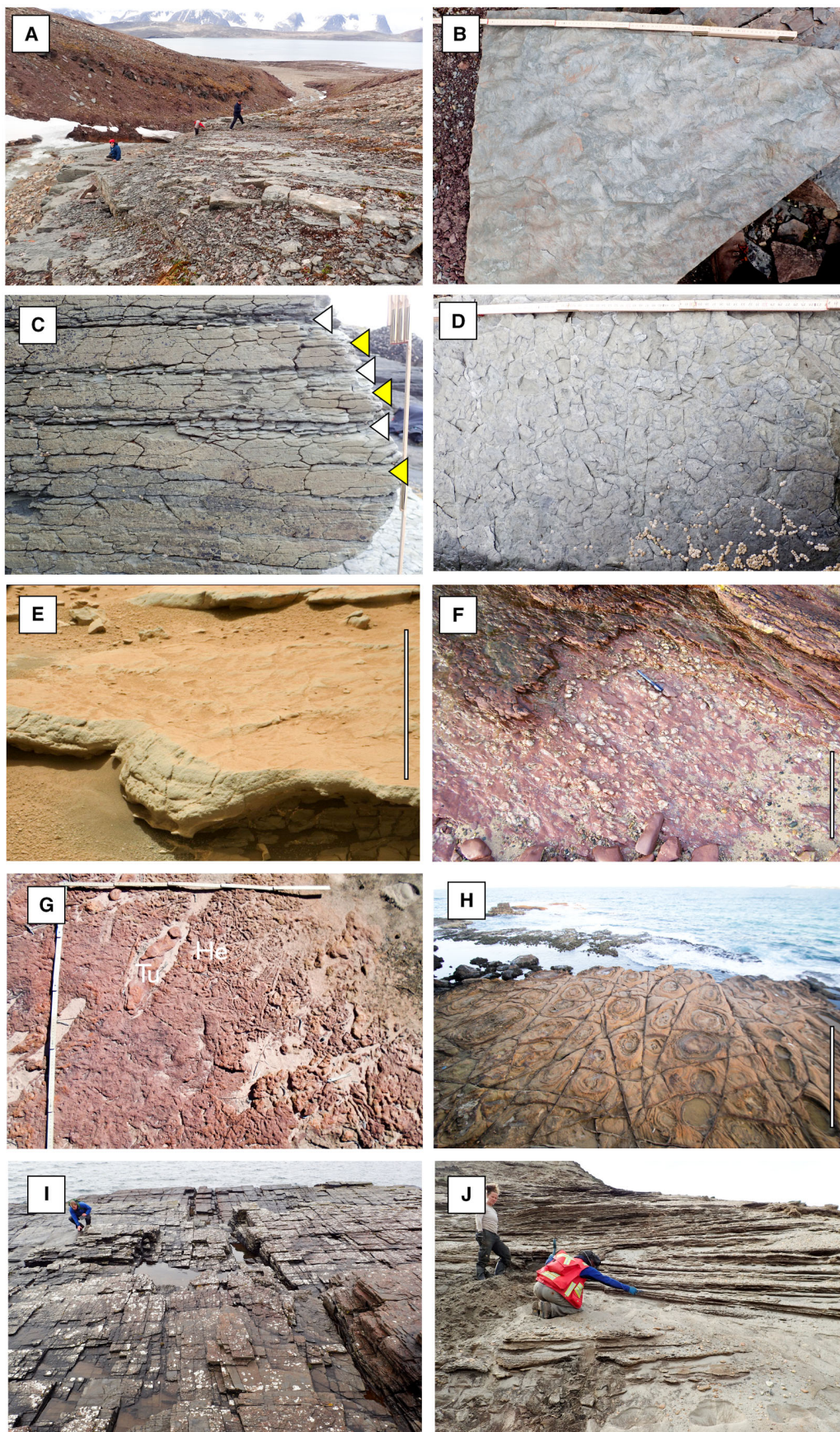


Fig. 6. Examples of non-genetic bedding planes arising from different causes. (i) *Due to irregular recent weathering of outcrop.* (A) and (B) Well-exposed and superficially bedding plane-abundant succession of sandstones and siltstones in the Lower Devonian Fränkelryggen Formation, Raudfjorden, Spitsbergen. Majority of bedding planes are actually non-genetic bedding planes (irregular sections through multiple laminae internal to beds, due to recent frost spalling) as seen in (B) (visible part of metre-stick is 1 m long). (C) and (D) Heavily fractured and jointed succession of heterolithic very fine-grained sandstone (yellow arrows) and siltstone (white arrows). In vertical section (C) colour and grain-size changes pick out primary stratification, but recent weathering picks out secondary fractures. Horizontal exposure (D) reveals non-genetic bedding plane has arisen due to weathering along secondary fractures rather than primary beds or laminae. Lower Devonian Kerrera Formation, Isle of Kerrera, Scotland (visible part of metre-stick is 35 cm). (E) Non-genetic bedding plane in the 3.5 Ga old Gillespie Lake Member, Gale Crater, Mars (NASA Curiosity Rover Mastcam image 0126MR078200300E1_DXX). Noffke (2015) considered this surface to potentially be a true substrate of fossilized extra-terrestrial microbial mats, but Davies *et al.* (2018) showed it has a greater similarity to non-genetic bedding planes arising from the degradation of bedding planes by recent aeolian abrasion on Earth (scale bar is 50 cm long). (ii) *Due to greater resistance of syn-depositional and post-depositional features internal to beds.* (F) Calcrete horizon, developed at depth within a palaeosol, providing a resistant non-genetic bedding plane, exposed by recent erosion. Lower Devonian Traeth Lligwy Beds, Anglesey, Wales (scale bar is 50 cm). (G) Extensive burrows internal to an original bed (shown by truncation and palimpsesting of *Tumblagoodichnus* (Tu) over *Heimdallia* (He). Porous burrow infill has been more effectively strengthened by secondary cements during diagenesis, providing a resistant non-genetic bedding plane, exposed by recent erosion. Silurian Tumblagooda Sandstone, Kalbarri National Park, Western Australia (visible horizontal part of metre-stick is 1 m long). (H) Enigmatic concretionary horizon apparently developed during late diagenesis and providing a resistant non-genetic bedding plane. Permian Broughton Formation, Wollongong Lighthouse, New South Wales, Australia (scale bar is 1 m). (iii) *Contrasting problems of bedding plane identification in indurated and unconsolidated sediments.* (I) Well-indurated, jointed and cleaved rocks often form continuous horizontal exposure that are an amalgam of patches of bedding surfaces that formed at different times: as a whole these may be considered non-genetic bedding planes with isolated fragments of true substrates or other bedding surfaces. Neoproterozoic Diabaig Formation, Rubha Dub Ard, Scotland. (J) Unconsolidated sediments most frequently lack visible bedding planes even where vertical bedding contacts are prominent: the granular nature of the sediment means that true substrates can rarely be excavated, and sedimentary grains reorganize into piles through collapse. Pliocene Beaufort Formation, Ellesmere Island, Nunavut, Canada.

level of the preserved bedding plane [for example, as in a scenario of slow sedimentation with continual overprinting and reworking by bioturbation (e.g. Savrda, 2014)]. Examples of palimpsest bedding planes are shown in Fig. 11, where many retain signatures of value for interpreting palaeoenvironments, but with a smudged temporal fidelity.

Palimpsest bedding planes are an imperfect but useful classification, arising from the practical necessity to consider D, E and S beyond the 'point' scale in natural outcrops (see *Evidence for sedimentation states in natural rock outcrops*). They are differentiated to account for the condensed and overlapping record of elapsed time in strata, and in recognition of the fact that, even where diagnosis is not hampered by under-determination, the boundaries of the classifications that can be applied to bedding planes can be fuzzy (Fig. 4). In palaeoenvironmental analyses, the degree of palimpsesting may be sufficiently negligible, or readily disentangled, that some palimpsest bedding planes can have comparable value to true substrates (Fig. 12).

Time significance of different types of bedding surfaces

A value of differentiating types of bedding surface is that it can provide new perspectives on the time significance of sedimentary strata at outcrop, which is not always possible from beds (Davies *et al.*, 2019). Physical bed thickness has no consistent relationship to time (Tipper, 2016), and it is widely accepted that time elapsed during the accrual of preserved sediment is grossly inferior to that elapsed during the accrual of non-preserved sediment and stasis (e.g. Barrell, 1917; Ager, 1981, 1993; Sadler, 1981; Dott, 1983; Miall, 2016a,b; Paola *et al.*, 2018; Straub *et al.*, 2020). Bedding surfaces are thus contemporaneous with most of the time elapsed between the deposition of the very earliest-deposited and very latest-deposited grains of sediment within an outcrop. Classifying them can refine understanding of the time elapsed during the accrual of outcropping strata, because different bedding surfaces have different temporal implications (Fig. 13). Depositional and constructed bedding surfaces must have been created near-instantaneously (although the

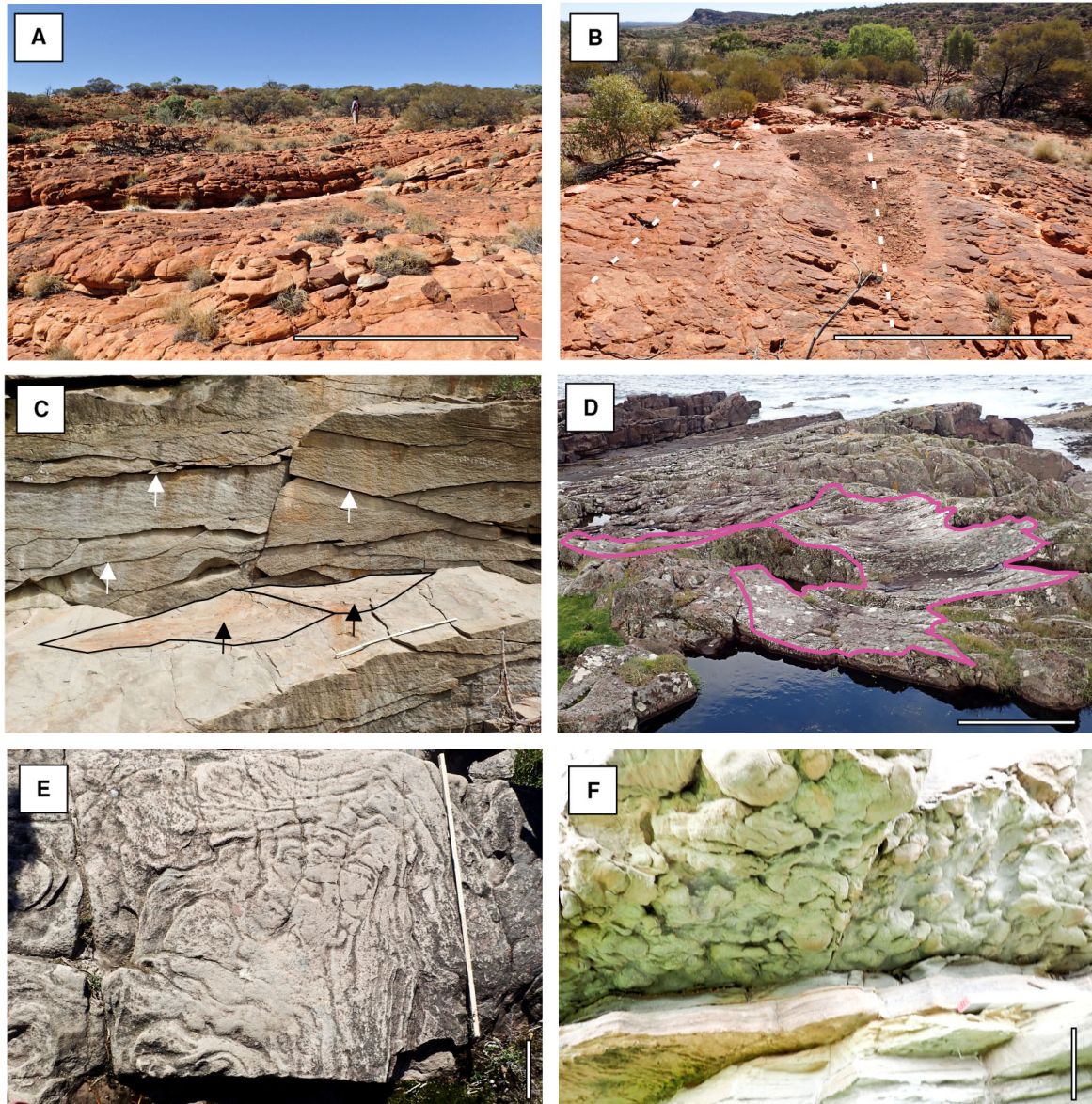


Fig. 7. Examples of constructed bedding planes. (A) and (B) Constructed bedding plane arising from near synchronous scour-and-fill at base of amalgamated dune cross-sets, preserving a scoop-shaped topography. Photographs of same outcrop looking up-palaeoflow (A) and down-palaeoflow (B). In (A) concave-up bedding contact (constructed topography) can be seen re-entering into cliff-face. In (B) the constructed bedding plane, exhibits two adjacent and parallel concave-upward scoops, the axes of which are shown by dashed lines. Arrow points to intersection of constructed bedding plane with constructed topography of small vertical part of outcrop. Silurian Mereenie Sandstone, Tjinjit Tjinjit, Northern Territory, Australia (scale bar is 2 m). (C) Trough cross-beds showing constructed bedding planes (white arrows) and equivalent constructed topography in vertical exposure (black arrows). Devonian Battery Point Formation, Seal Rock, Gaspé, Québec, Canada (stick is 1 m long). (D) Laterally-amalgamated scoop-shaped constructed bedding planes formed by migrating three-dimensional dunes within in-channel fluvial facies (example highlighted in pink). Neoproterozoic Applecross Formation, Culkein, Scotland (scale bar is 1 m long). (E) Characteristics of constructed bedding planes include surface preservation of truncated in-bed fabrics: example here shows constructed bedding plane formed by erosion of a previously interbedded layer that had already experienced soft-sediment deformation, late Silurian Serra Sandstone, Wonderland Walk, Victoria, Australia (stick is 1 m long). (F) Constructed bedding planes can be formed *in situ* as well as through syn-depositional erosion: in this example, the basal expression of a bedding plane reveals an irregular surface developed by sand-grade sediment loading into a wet mud-grade sediment at the time of deposition. Lower Devonian Lower Caithness Flagstone Group, Ballygill, Scotland (scale bar is 20 cm long).

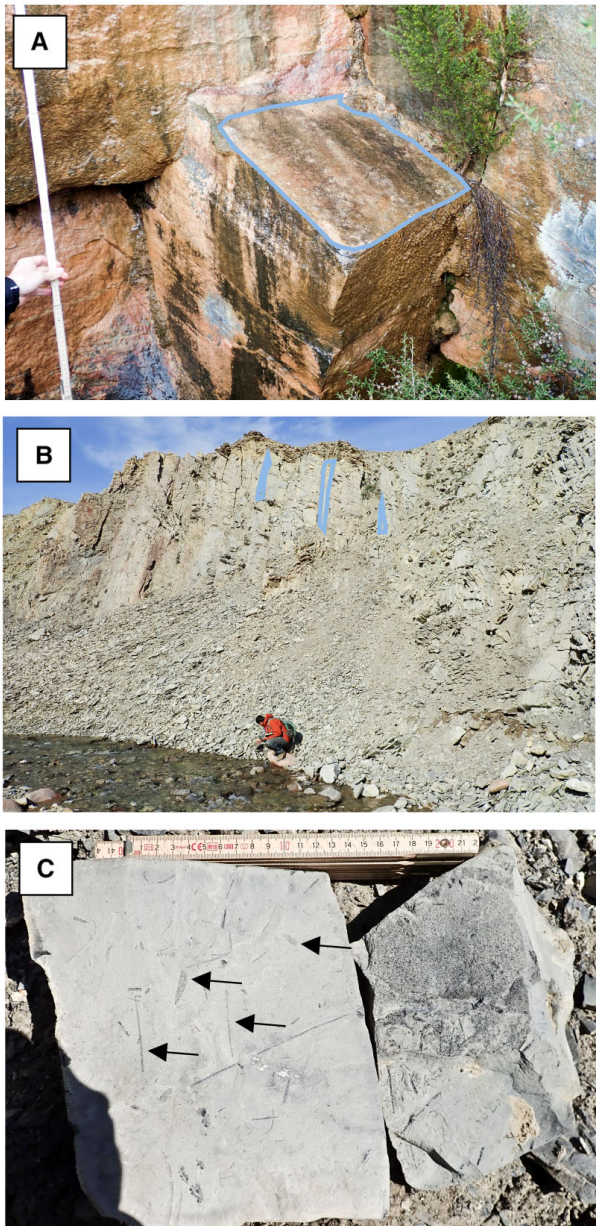


Fig. 8. Examples of depositional bedding planes. (A) Synoptic topography that persisted for a geological instant as bedforms that migrated may have become exposed as depositional bedding planes. In this example the inclined foreset of a migrating subaqueous dune has been randomly exposed as such (highlighted blue), amongst many other inclined foresets which could potentially have acted as planes of weakness along which the bedding could split. Late Silurian Major Mitchell Sandstone, Mount William, Victoria, Australia (visible part of metre-stick is 80 cm long). (B) and (C) Fine-grained sediment that settled out of suspension under conditions of near-continuous deposition can split along lamina planes (highlighted blue), in fissile successions of shale. The synchronicity of the surfaces is apparent from split blocks, such as those shown in (C) where pelagic fossils (black arrows pointing to graptolites in this example) are preserved in entirety along horizontal planes (i.e. as opposed to being slightly inclined and partially buried by sediment). Silurian Cape Phillips Formation, Ellesmere Island, Nunavut, Canada; measuring stick in (C) is 20 cm long.

Diachroneity of bedding surfaces

Bedding surfaces at outcrop can have different classifications laterally, and diachroneity at the scale of walking distance is not unusual (Fig. 15). This is an inevitable artefact of the way in which bedding surfaces are created as a sediment pile accrues, particularly in patches of limited local accommodation or sediment supply. Surface amalgamation or the reactivation of former surfaces at the sediment–water/sediment–air interface can mean that an apparently contiguous bedding surface is a product of multiple events, disconnected in time (e.g. Holbrook, 2010; Gani, 2017). This does not affect investigations at a smaller scale (i.e. a patch of true substrate with palaeoenvironmental information can still be a faithful record even if it passes laterally into a constructed bedding plane) but can affect interpretations of the temporal (dis)continuity of larger exposures.

IDENTIFICATION AND INTERPRETATION OF TRUE SUBSTRATES

With the caveats and distinctions outlined in the previous section in place, for the remainder of this paper attention is focussed on true substrates, which, from their archived structures, have the potential to provide unique insights

latter must also have erased an uncertain volume of previously accrued temporal records). In contrast, the temporal persistence of true substrates varies depending on environmental controls on the duration of stasis, and palimpsest bedding planes represent condensed temporal records. Appreciating the range of surfaces at outcrop (Fig. 14), the analogy of the SSR as a tape recorder (e.g. Straub *et al.*, 2020), is readily applied: stratigraphic time has variably been faithfully recorded (depositional bedding planes and D–S–D true substrates), rewound and recorded over (constructed bedding planes and D–E–S–D true substrates), or fast-forwarded (palimpsest bedding planes).

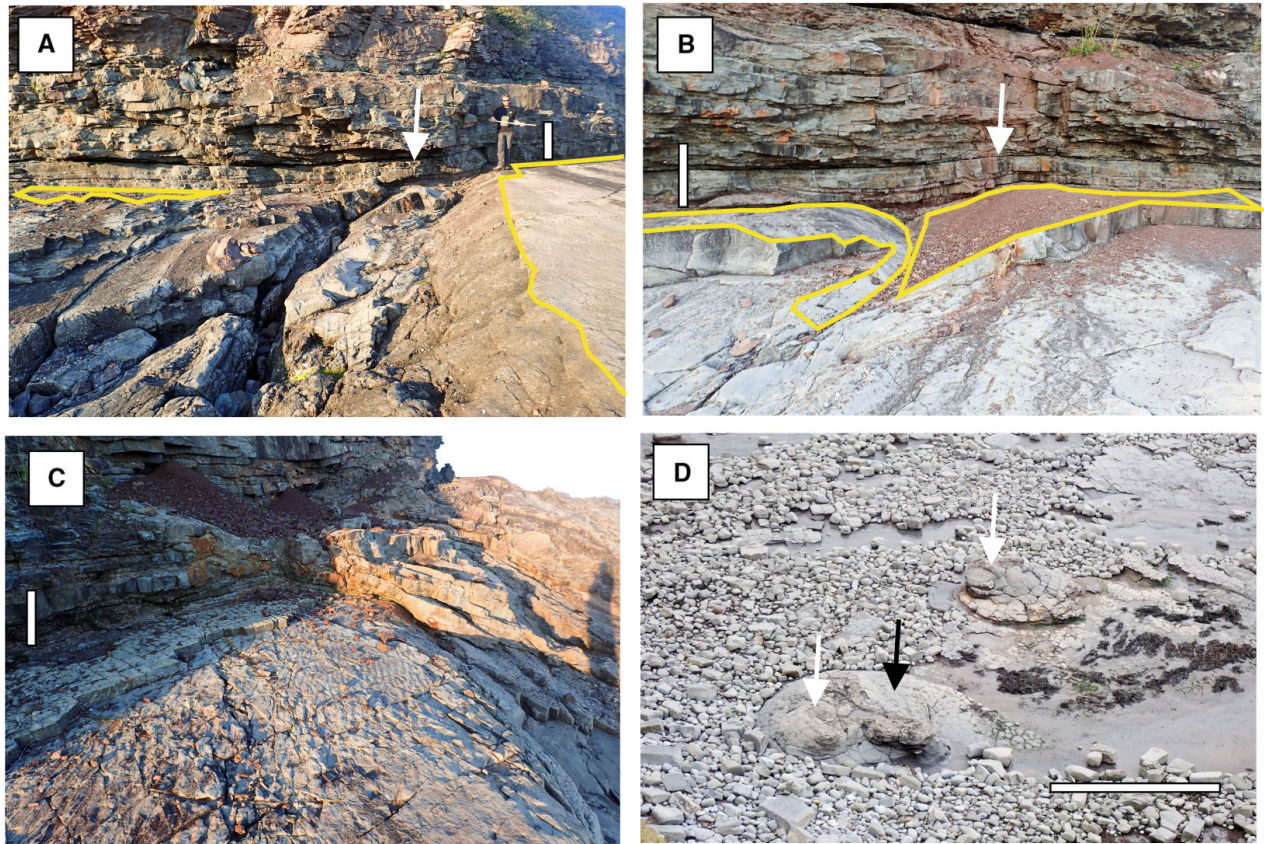


Fig. 9. Physical evidence for D-S-D true substrates (see also features in Fig. 1; scale bar in each image is 1 m). (A) to (C) The ‘earthquake bed’ in the Pennsylvanian Tynemouth Creek Formation, New Brunswick, Canada, showing synoptic topography of two syn-depositional 90 cm high fault scarps in alluvial strata that were later draped by subsequent strata (arrowed). Surface highlighted in yellow (discontinuous as partially recently eroded) is thus a true substrate that existed as the land surface prior to deposition of overlying sediment. Ripple marks (C) and vertical burrow tops can be recognized on this surface. See *Plint (1985)* for more locality details. (D) Partly eroded tops of mud volcano structures in the Lower Jurassic Lias Group, Kilve, Somerset, England. The flanks of the volcano structures are non-genetic bedding planes, formed by recent erosion through interbedded limestone and shales, but the tufa caps to the structures (white arrows) indicate that the bedding plane extending from this point (black arrow) may be a D-S-D true substrate that once provided the seabed through which the mud volcanos breached. See *Price *et al.* (2008)* for more locality details. Scale bar in all images is 1 m.

into ancient sedimentary environments (e.g. *Donovan, 2014*).

The identification of true substrates is reliant on the preservation of surficial sedimentary characteristics, such as those listed in Table 2. These are largely those structures that have been classified as ‘pre-burial’ sedimentary structures (*Picard & High, 1973*), and many form in the sediment active layer during the very earliest stages of diagenesis (i.e. whilst the host bed is undergoing physical reduction in porosity through consolidation and compaction; *Wheatcroft *et al.*, 2007*). All of these features are likely to persist on a true substrate after they have been lithified, even

though some tectonic distortion can happen after lithification [this can be retrodeformed visually (e.g. *Johnson *et al.*, 1994*; *Fichman *et al.*, 2015*) and does not diminish their significance].

Palaeoenvironmental significance of diagnostic features

True substrate features (Table 2) can be interpreted in terms of the palaeoenvironmental conditions during, and temporal duration of, stasis (Fig. 16). For example, a true substrate yielding flat-topped ripples, foam marks, rill marks, desiccation cracks or raindrop impressions could

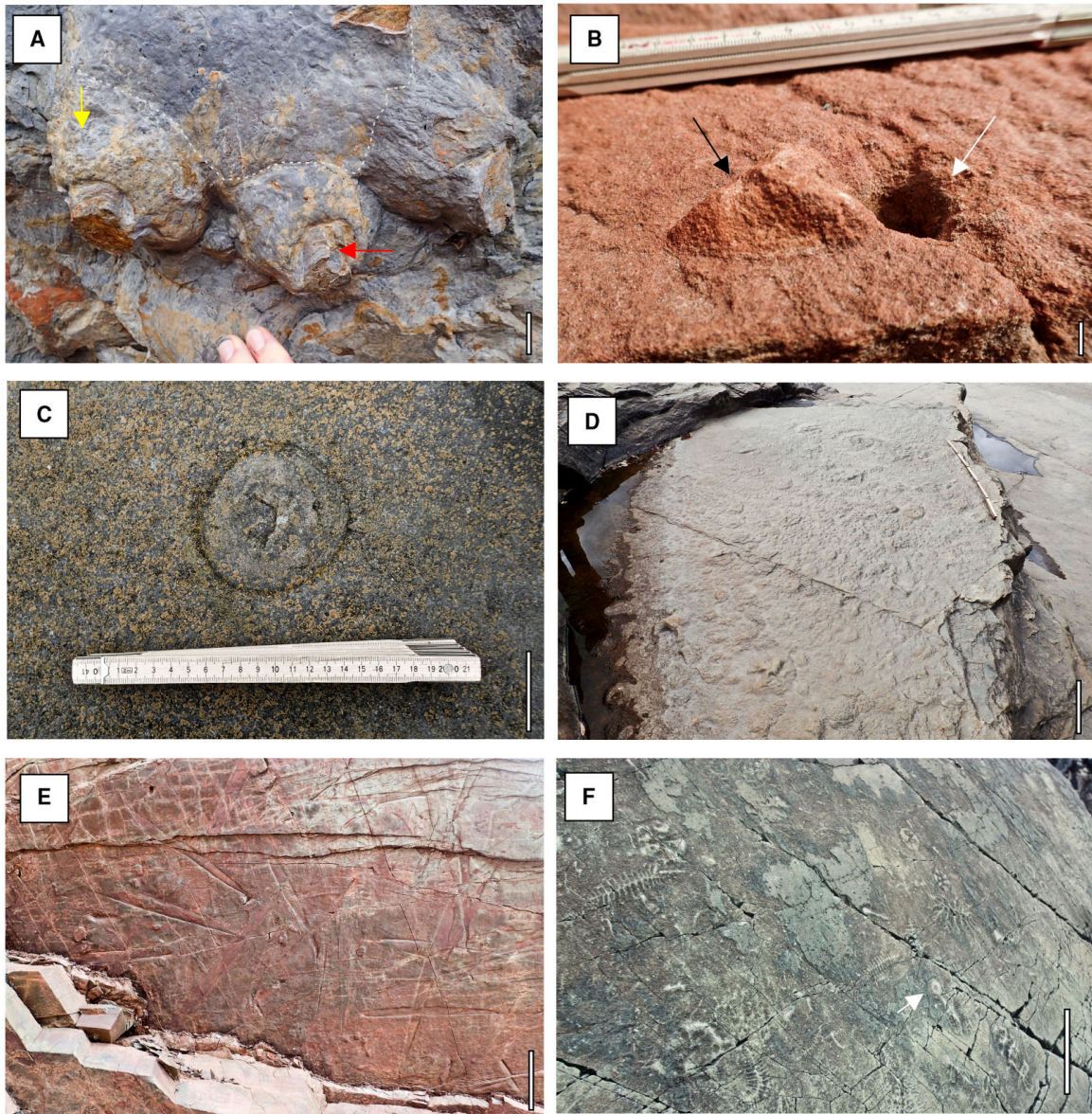


Fig. 10. Palaeontological evidence for D-S-D true substrates. (A) Dinosaur footprint (? *Caririchnium*) preserved as a positive hyporelief cast of a true substrate. Footprint can be determined to not be an undertrack by presence of impressions of skin scales (yellow arrow) and claw texture (red arrow; note that area above dashed line is part of the underlying layer, still adhering to the footprint). Lower Cretaceous Ashdown Formation, Fairlight, Sussex, England (for more details see Shillito & Davies, 2019a; scale bar is 20 cm). (B) Arthropod excavation trace fossil (*Trusheimichnus*) where both excavated sediment (black arrow) and hollow (white arrow) are preserved, respectively, in positive and negative epirelief on the same surface. Silurian Tumblagooda Sandstone, Kalbarri National Park, Western Australia (for more details see Shillito & Davies, 2020; visible part of ruler is 20 cm). (C) to (D) Casts of jellyfish imply beach-stranding and sand-casting, and occur throughout the Phanerozoic: singular example from Late Silurian Holmestrand Formation, Jeløya, Norway: (C) see Davies *et al.* (2005) for details (visible part of ruler is 20 cm) – multiple stranded jellyfish on surface also patterned by adhesion ripples, implying mass stranding on emergent true substrates of the Cambrian Potsdam Sandstone, Ausable Chasm, New York, USA; (D) see Hagadorn & Belt (2008) for details (ruler is 1 m long). (E) Hyporelief cast of non-marine true substrate, revealed by overlapping and randomly oriented fallen fronds of a cordaitalean tree, on a surface also containing drip impressions indicative of water and leaf debris falling from a nearby tree. Pennsylvanian Tynemouth Creek Formation, Gardner Creek, New Brunswick, Canada (scale bar is 1 m). (F) True substrate as an archive of palaeontological data from the Ediacaran Mistaken Point Formation, Mistaken Point, Newfoundland, Canada. Soft-bodied organisms, some still attached to holdfasts (arrowed) provide snapshots of contemporaneous communities that can yield palaeoecological information (e.g. Mitchell *et al.*, 2020; scale bar is 50 cm).



Fig. 11. Examples of palimpsest substrates that archive non-contemporaneous sedimentary signatures. (A) to (D) Desiccation cracks are common features of palimpsest substrates due to their propensity to penetrate multiple layers. Without direct evidence of being the topmost layer (and therefore true substrates), they may appear in multiple layers that themselves never dried out. (A) is determined to be a ripple-marked and desiccated true substrate because cracks exhibit upturning of rippled beds at margins (black arrow) and no layers higher in the sequence are cracked. However, crack pattern penetrates downward into sediments below (white arrow) creating palimpsest substrates. Late Carboniferous Parrsboro Formation, West Beach, Nova Scotia, Canada (measuring stick is 1 m long). (B) shows plan-view expression of two desiccation cracks (d1 and d2) exposed on multiple non-genetic bedding planes, arising from the fissility of the mudrock lithology. Crack dimensions diminish on lower exposed laminae. Neoproterozoic Diabaig Formation, Loch Diabaig, Scotland (scale bar is 20 cm long). (C) Example of desiccation cracks that have penetrated down from above layers and offset arthropod trackways that were emplaced on an earlier true substrate. Lower Devonian Kerrera Formation, Isle of Kerrera, Scotland (visible part of measuring stick is 50 cm). (D) Hyporelief cast of partly eroded true substrate comprising partially eroded ripples that have been later deformed by the undertrack of an iguanadontid dinosaur, which itself pre-dates the deep penetrating desiccation crack (seen because the crack deflects at the footprint). Lower Cretaceous Ashdown Formation, Fairlight, Sussex, England (scale bar is 20 cm). (E) and (F) Palimpsest substrates developed on both depositional bedding planes (blue) and constructed bedding planes (purple; measuring stick is 1m long). (F) An enlargement of (E) showing dense truncated infaunal horizontal burrows that have equally exploited both types of surface. This implies that the burrows were imparted while both types of surface were interred but provided planes of weakness or subsurface resource accumulations within the sediment pile. Early Permian Cape John Formation, Cape John, Nova Scotia, Canada. (G) and (H) Example of palimpsesting where long axis-vertical glacial dropstones have been partially draped by successive layer of sediment. Influence of glacial dropstones persisted, as seen in (H) where *Diplichnites* trackway on true substrate is forced to skirt around exposed part of dropstone (direction of travel arrowed: dropstone is that which is arrowed in (G)). Late Ordovician Table Mountain Group, Matjiesgoedkloof, Western Cape, South Africa (see Davies *et al.*, 2020b for further details; measuring stick is 20 cm long).

indicate that stasis persisted during an interval of subaerial exposure (Allen, 1985), and facies signatures elsewhere in the host succession can be used to abduce the likely timescale of exposure (for example, diurnal tidal settings versus seasonal floodplain settings).

The specific palaeoenvironmental value of signatures on true substrates can be variable, and sometimes hindered by equifinality (Davies *et al.*, 2016, 2020a) whereby structures can be interpreted to have had one of multiple potential formative origins and the specific cause cannot be unequivocally diagnosed. Despite this, many surface features can provide more or less certainty about the nature of true substrates, particularly when multiple features can be seen to have developed at different times in a prolonged interval of net stasis (Fig. 16).

The commonality of the features listed in Table 2 is partly dependent on likelihood of preservation and may not reflect their frequency in the SSR. For example, at the present-day, glacial dropstones are restricted to mid-high latitude belts, but rill marks can be found on almost every beach, river and lakeshore between the equator and poles. Yet due to the resilience of dropstones against reworking, and the fully eroded end state of rill marks, ancient instances

of the former outnumber the latter in the SSR (for example, Fig. 11G). However, the presence of some rill marks in the rock record (for example, Fig. 1E) shows that there are very few surficial sedimentary structures that have zero potential for preservation. Some of the most common and significant indicators of stasis and true substrates are included below.

Ripple marks

Ripple marks are generated in the surface active layer by flow regimes just above the critical shear stress, while bedforms are in equilibrium (Wheatcroft *et al.*, 2007; Perron *et al.*, 2018). Although ripple formation may also occur during continuous deposition (for example, climbing ripple lamination), when seen in full relief on a bedding plane it is most probable that the formation of those particular ripple marks developed shortly before the onset of an interval of stasis – especially if there is evidence for the registration of additional signatures (for example, arthropod trackways) or modification of the ripple-marked substrate (for example, drainage marks). Ripple marks can provide evidence of palaeohydraulic regime just before and during stasis (e.g. Perron *et al.*, 2018; Fig. 17), and their uneven distribution within a lithologically-similar section may

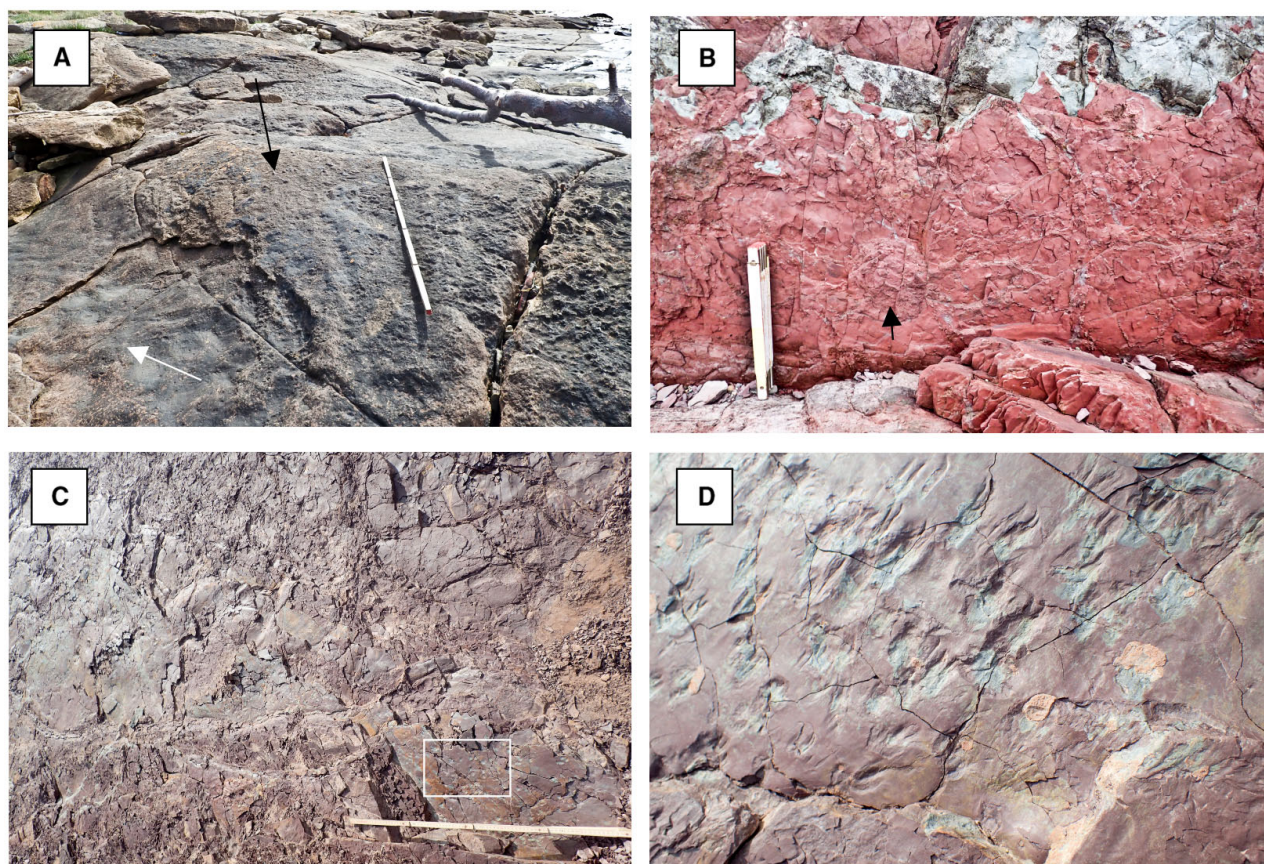


Fig. 12. Examples of bedding surfaces at outcrop where aspects of true substrates can be recognized despite having been palimpsested. (A) Large *Diplichnites* trackway (black arrow) imprinted to shallow depth on the flank of a small convex-up dune. In the adjacent dune trough, ripple marks are visible (white arrow). The shallow depth and absence of detail implies that these tracks are probably undertraces, and they appear to be on a different lamina to the ripple marks. However, the dune topography must have persisted when the tracemaker crossed the substrate as the tracks are inclined upslope and evenly deep. The surface is thus not a true substrate, but deposited laminae were sufficiently thin to render the palimpsest substrate an accurate record of a large myriapod crossing a damp dune. Mississippian Anstruther Formation, Kingsbarns, Fife, Scotland (metre stick for scale). (B) Apparent true substrate of ripple-marked mudrock that has been palimpsested by multiple other signatures from an above layer including penetrative desiccation cracks and large *Beaconites* burrows (arrowed). Late Silurian Moor Cliffs Formation, Manorbier, Pembrokeshire, Wales (measuring stick is 20 cm long). (C) and (D) Non-genetic bedding plane comprising multiple fragments of very finely-laminated mudrock true substrates [area of image (D) shown in white box in (C)]. The surface as a whole is an amalgam due to recent erosion, but at small scales, fragments of true substrates can be identified: such as the tetrapod trackways seen in (D). Mississippian Pomquet Formation, Cape Breton Island, Nova Scotia, Canada. Visible part of metre stick in (C) is 80 cm long.

assist in differentiating regions dominated by stasis (ripple marks present) from regions dominated by erosion (ripple marks absent), where energy was channelized within a sedimentary system (e.g. Muhlbauer *et al.*, 2020).

Raindrop impressions

Raindrop impressions must indicate stasis as they can only be imparted on a substrate during an interval of non-deposition. The features have

proved historically controversial, with some authors denying they have preservation potential (Buckland, 1842; Picard & High, 1973; Moussa, 1974), and others illustrating their appearance in the SSR (Lyell, 1851; Metz, 1981; Rubin & Hunter, 1984; Robb, 1992). Experimental work has shown that raindrop impressions are distinguished by having a greater radius of curvature than their horizontal and vertical dimensions, distinguishing them from spherical

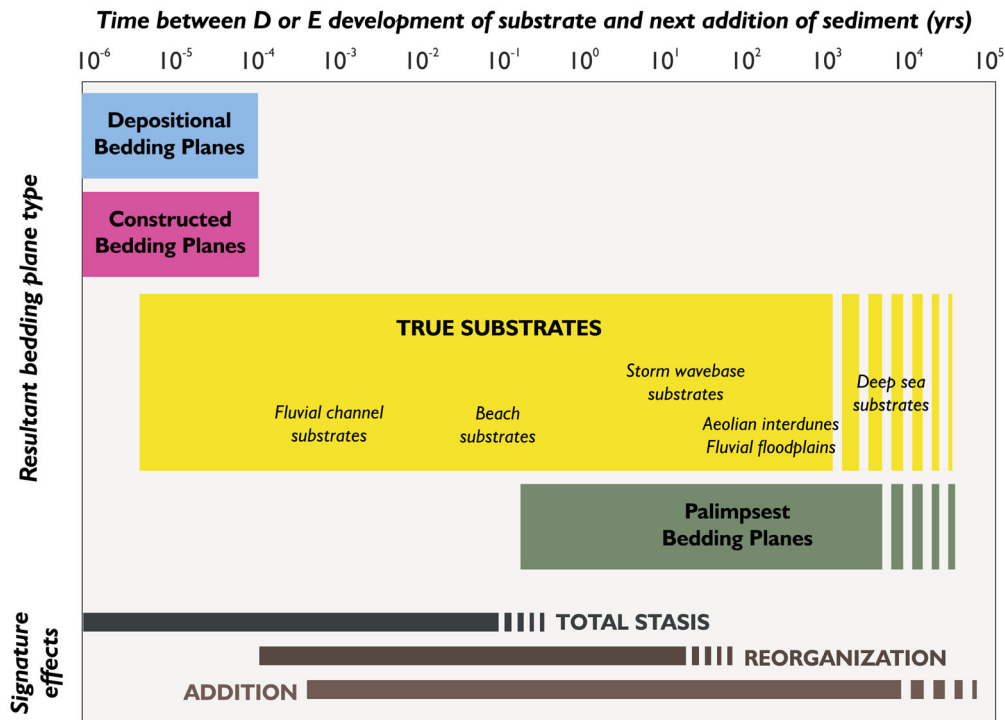


Fig. 13. Temporal context of true substrates amongst other bedding plane types that may get interred after their initial topographic creation by E or D, showing effects of prolonged persistence of substrates on bedding plane signatures. Where substrate persists only instantaneously, resultant bedding plane will be either depositional (D–D–D) or constructed (D–E–D). Stasis for longer than this permits true substrates to develop – the length of time a substrate persists depends on environmental setting. Regardless of time spent in stasis, if the substrate is eventually exhumed, the time-bar at the top of the figure is considered to reset. Signatures on substrates may remain in total stasis, where there is no change to their form since creation: the upper temporal limit of this state is determined by the potential for ambient environmental factors to add signatures or reorganize the surface. Alternatively, substrates may undergo reorganization without significant net addition or removal of sediment across the area of the substrate; or substrates may see the incremental addition of new sedimentary signatures.

degassing bubbles (Zhao *et al.*, 2019). Abundant observed features in the SSR fit this criterion (for example, Fig. 1A), emphasising that many true substrates do counterintuitively preserve extremely delicate surface features.

Mudcracks

Mudcracks due to desiccation, syneresis and other processes (e.g. Cowan & James, 1992; Hara-zim *et al.*, 2013; Kovalchuk *et al.*, 2017) are common in the SSR and can only form during stasis. However, they do not always indicate the presence of a true substrate, as they penetrate downward and so, in truncated form, are also common constituents of underlying palimpsest bedding planes and non-genetic bedding planes (for example, Fig. 11A to G). Accessory evidence is required to show that the desiccated bedding plane is a true substrate. This is particularly important when attempting to use crack

morphology (for example, angle of bifurcation) to determine crack origin (e.g. Kovalchuk *et al.*, 2017), because such characteristics may differ between a desiccation crack at a true substrate and the partially truncated crack at depth on a palimpsest or non-genetic bedding plane.

Animal tracks

Animal tracks and footprints can only be imparted onto substrates during stasis and can provide significant palaeoenvironmental insights (for example, Fig. 16). The fidelity of resolution of footprints that have been registered onto a substrate depends on several factors including animal anatomy and behaviour, substrate conditions and post-registration conditions (Davis *et al.*, 2007; Marchetti *et al.*, 2019). Many of these factors determine footprint quality at the time a substrate was interred; thus, anatomically imperfect footprints can still be constituents of a

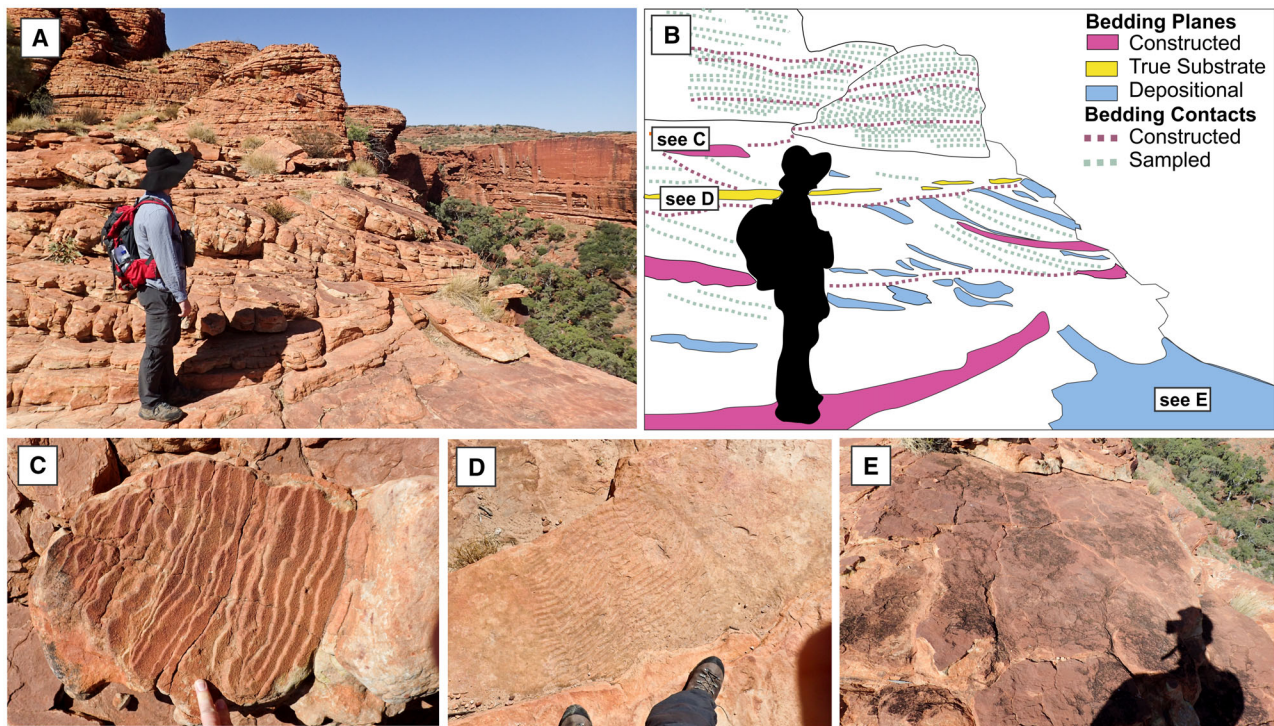


Fig. 14. Outcrop containing depositional bedding planes, constructed bedding planes and true substrates within the same succession, indicative of intermittently mobile aeolian dunes (see Shillito & Davies, 2021). Silurian Mereenie Sandstone Watarrka National Park, Northern Territory, Australia. (A) and (B) Outcrop image and sketch showing nature of visible bedding surfaces and location of close-up images in (C) to (E; geologist for scale is 1.8 m). (C) Constructed bedding plane showing truncated foresets. (D) True substrate with patch of ripple marks. (E) Depositional bedding plane showing foreset dipping towards camera.

true substrate, and yield palaeoenvironmental information about stasis. For example, gentle currents can cause organisms to apply more or less weight onto sediment as they are tilted by the current, resulting in uneven and distorted trackways (Uchman *et al.*, 2018; Getty, 2020).

A significant perceived issue with animal tracks is that many surface trackways also result in undertracks at depth (Goldring & Seilacher, 1971; Falkingham & Gatesy, 2014), the recognition of which would only indicate palimpsest or non-genetic bedding planes and not true substrates (Frey & Pemberton, 1985). It has been suggested that any animal trackway that is preserved in the rock record, and which did not have special preservation conditions such as the presence of surface biofilms, is most likely to be an under-track (Seilacher, 2007, 2008). However, while certain taphonomic pathways do stabilize surface tracks (e.g. Davis *et al.*, 2007; Scott *et al.*, 2010), they are not prerequisite, contrary to what Seilacher (2007, 2008) envisaged (see *Preservation of true substrates*). Rare instances of fully preserved

mortichnia, where the fossilized tracemaker is found dead at the end of the trackway (e.g. Lomax & Racay, 2012) are alone proof that not all trackways are partially-exhumed undertracks. The surficial nature of animal tracks can sometimes be indicated by their definition, and instances of tracks and undertracks on the same bedding plane are known (Shillito & Davies, 2019a), producing palimpsest bedding planes that can still be partially read as true substrates (for example, Fig. 11D).

Burrows

As infaunal constructions, not all burrows record true substrates, but some may have characteristics that permit their identification. Openings of vertical burrows observed on a bedding plane can be identified as contemporaneous with a true substrate if they exhibit a combination of features such as no overlapping, equant spacing to avoid competition, distinct sediment composition to burrow fills, or mounds of excavated sediment around the burrow aperture

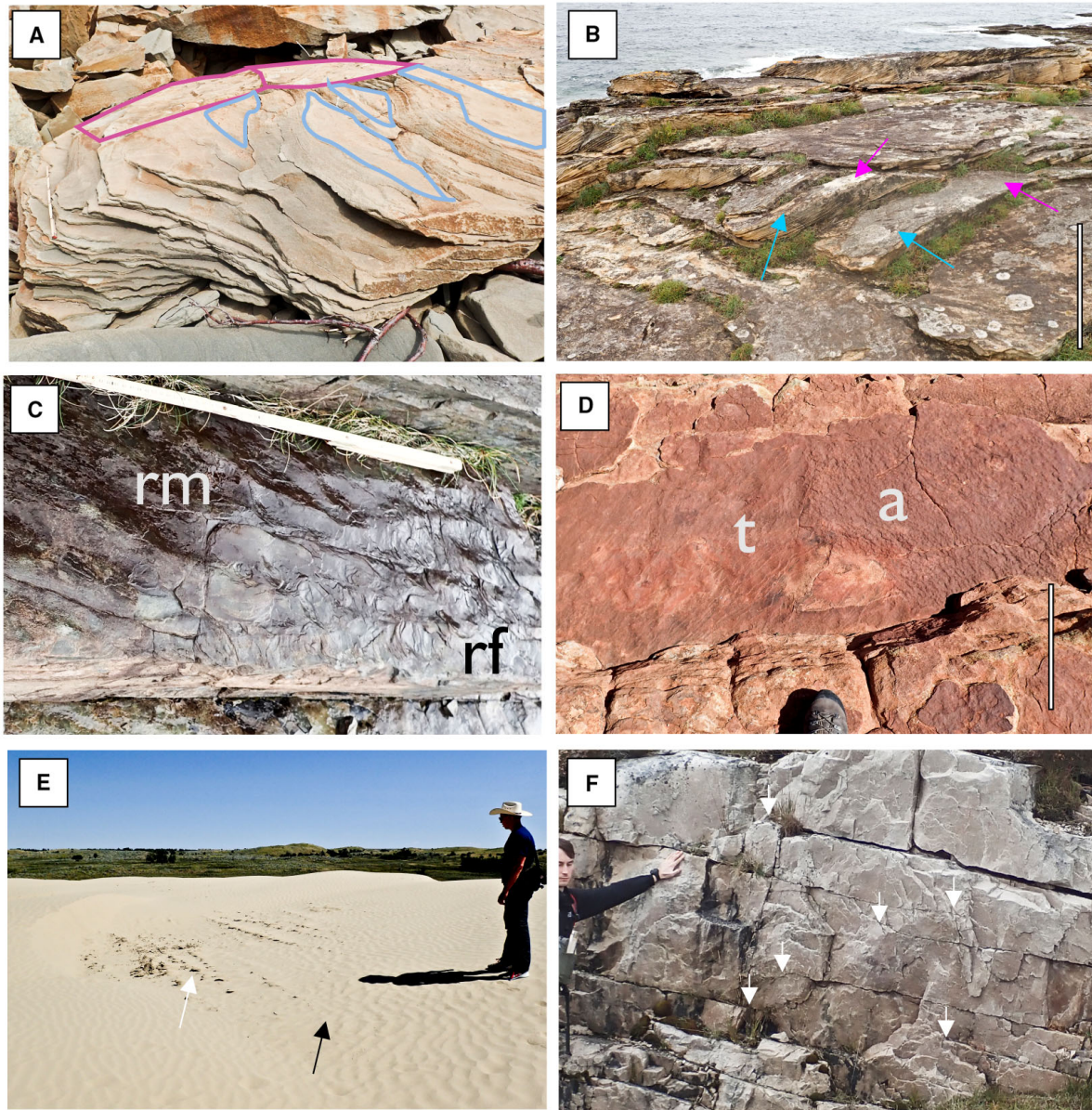


Fig. 15. Examples of lateral discontinuity and transition between different types of bedding surface. (A) Lateral transition from constructed bedding plane (purple) to depositional foreset bedding planes (blue) within amalgamated cross-beds of fluvial in-channel facies. Devonian Battery Point Formation, Seal Rock, Gaspé, Québec, Canada (stick is 1 m long). (B) Outcrop photograph showing how amalgamated bedding planes can transition laterally from depositional bedding planes (blue arrow) to constructed bedding planes (purple arrow). In-channel fluvial facies of the Mississippian Stainmore Formation, Howick, Northumberland, England (scale bar is 1 m long). (C) Lateral transition from true substrate recorded by ripple marks (rm) to constructed bedding plane recorded by syn-depositional truncation of ripple marks to rib and furrow pattern (rf). Neoproterozoic Rubha Dubh Ard Member, Badenscallie, Scotland (visible part of ruler is 60 cm long). (D) Lateral transition between true substrate [with adhesion marks (a)] and apparent constructed bedding plane [with truncated foresets (t)]. Aeolian facies of the Silurian Mereenie Sandstone Watarrka National Park, Northern Territory, Australia (scale bar is 50 cm long). (E) Modern analogue for image in (D), showing how truncated aeolian foresets (white arrow) can be D-E-S-D true substrates, grading laterally into more obvious ripple marked true substrates (black arrow), due to differential erosion and exposure of sediment piles. Great Sand Hills, Saskatchewan, Canada (geologist is 1.85 m tall). (F) Vertical expression of small-scale diachroneity: sampled topography bedding surfaces disappear laterally (white arrows) creating ‘hanging lines’ that record borders between areas of continual deposition and areas of temporary stasis within the shallow marine environment of deposition. Lower Cambrian Basal Quartzite Formation, Skiag Bridge, Scotland (geologist is 1.8 m tall).

Table 2. List and details of sedimentary structures that can be practically used to infer that a bedding surface is a true substrate. Formative interval refers to whether the feature is imparted to a bedding surface during an interval of stasis (S), or whether it can be a relict feature of deposition (D), erosion (E) or transport (T), that has persisted during an interval of stasis. Type of feature refers to whether the feature is usually singular or pervasive on a surface. Frequency of features in rock record is classified as: ‘Very Common’ (i.e. facies-crossing, frequently observed); ‘Common’ (i.e. frequently observed but requiring particular environmental facies); and ‘Rare’ (i.e. uncommonly observed due to low preservation potential or being highly facies-specific). Time taken to form features is coded as follows: 1 – seconds to minutes (for example, instantaneous with deposition); 2 – hours to days (for example, where feature requires changing conditions, such as draining water for ladder ripples); 3 – up to years or more (for example, when feature requires a long-term biological or chemical process). Maximum persistence on substrates after their formation is coded as follows (note these estimates are generalized given variability of some of the listed features): 1 – up to days (for example, where feature is formed in granular sediment and prone to reworking when substrate conditions such as dampness change); 2 – up to weeks (for example, where feature is prone to reworking, but leaves a pronounced microtopographic effect); 3 – up to months (for example, where feature is very pronounced, or typically formed on cohesive substrates); 4 – up to years or more (for example, where feature is a result of a long-term biological or chemical process).

	Formative interval	Type	Frequency of occurrence	Time taken to form feature	Maximum persistence as true substrates	Evidence for true substrate
<i>Surface features which exclusively represent true substrates, except in special circumstances</i>						
Primary current lineation	Relict D	Pervasive	Very common	1	1	Unless immediately followed by further deposition
Surficial MISS	S	Pervasive	Very common	3	4	Exclusively formed during stasis
Syneresis cracks	S	Pervasive	Very common	2	3	Exclusively formed during stasis
Animal tracks and trails	S	Singular	Very common	1	3	Exclusively formed during stasis
Ladder ripple marks	Relict D	Pervasive	Common	2	2	Almost exclusively true substrates, formed during waning/negligible flow, post-D
Flat-topped ripple marks	Relict D	Pervasive	Common	2	2	Almost exclusively true substrates, formed post-D by negligible E (wind-shaving)
Surficial gas/air escape bubble marks	S	Pervasive	Common	2	4	Exclusively formed during stasis
Raindrop and haildrop impact marks	S	Pervasive	Common	1	3	Exclusively formed during stasis
Adhesion marks and ripples	S	Pervasive	Common	1	1	Exclusively formed during stasis
Drag marks	S (+T)	Singular	Common	1	3	Exclusively formed during stasis
Chevron marks	S (+T)	Singular	Common	1	3	Exclusively formed during stasis
Skip, prod and bounce marks	S (+T)	Singular	Common	1	3	Exclusively formed during stasis
Drip impressions	S	Singular	Common	1	2	Exclusively formed during stasis
Splash impressions	S	Singular	Common	1	2	Exclusively formed during stasis
Puddle topography	Relict E	Singular	Common	2	4	Unless immediately filled in by deposition

Table 2. (continued)

	Formative interval	Type	Frequency of occurrence	Time taken to form feature	Maximum persistence as true substrates	Evidence for true substrate
Obstacle scour marks	Relict E	Singular	Common	2	4	Unless immediately filled in by deposition
Obstacle shadow mounds (e.g. some VISS, setulfs)	Relict D	Singular	Common	2	4	Form indicates persistence during stasis
Water level marks	S	Pervasive	Rare	2	2	Exclusively formed during stasis
Swash marks	S	Pervasive	Rare	1	1	Exclusively formed during stasis
Rill marks	Relict E	Singular	Rare	2	3	Preserved due to cessation of erosion at surface, therefore true substrates
<i>In situ</i> fossils of sessile organisms	S	Singular	Rare	3	4	Exclusively formed during stasis
Surficial mineral pseudomorphs (e.g. salt, ice)	S	Singular	Rare	3	4	Exclusively formed during stasis
Volcanic ejecta impact impressions	S	Singular	Rare	1	4	Exclusively formed during stasis
Fault and microfault escarpments	S	Singular	Rare	1	4	Exclusively formed during stasis
Scratch circles	S	Singular	Rare	2	1	Exclusively formed during stasis
<i>In situ</i> ventifacts	S	Singular	Rare	3	4	Exclusively formed during stasis
<i>Surface features which most commonly represent true substrates, but require verification</i>						
Ripple marks (various forms)	Relict D	Pervasive	Very common	1	3	When uppermost rippled lamina with no evidence for truncation (i.e. rib and furrow)
Dune forms	Relict D	Pervasive	Common	1	3	When bed surface topography with no evidence for truncation
Hummock and swale forms	Relict D	Pervasive	Rare	1	3	When bed surface topography with no evidence for truncation
Antidune forms	Relict D	Singular	Rare	1	2	When bed surface topography with no evidence for truncation
<i>Surface features which do not exclusively represent true substrates but can be identified as such if seen in conjunction with Category A forms, or with alternative evidence</i>						
Desiccation cracks	S	Pervasive	Very common	2	4	When surface seen with Category A forms, or curled crack margins
Vertical burrow sections	S	Pervasive	Very common	2	4	With evidence for excavated sediment or aperture collapse
Truncated bedforms	E, or Relict E	Pervasive	Very common	1	3	When palimpsested with Category A forms
Groove marks	Relict E, or E + D	Singular	Common	1	3	When palimpsested with Category A forms

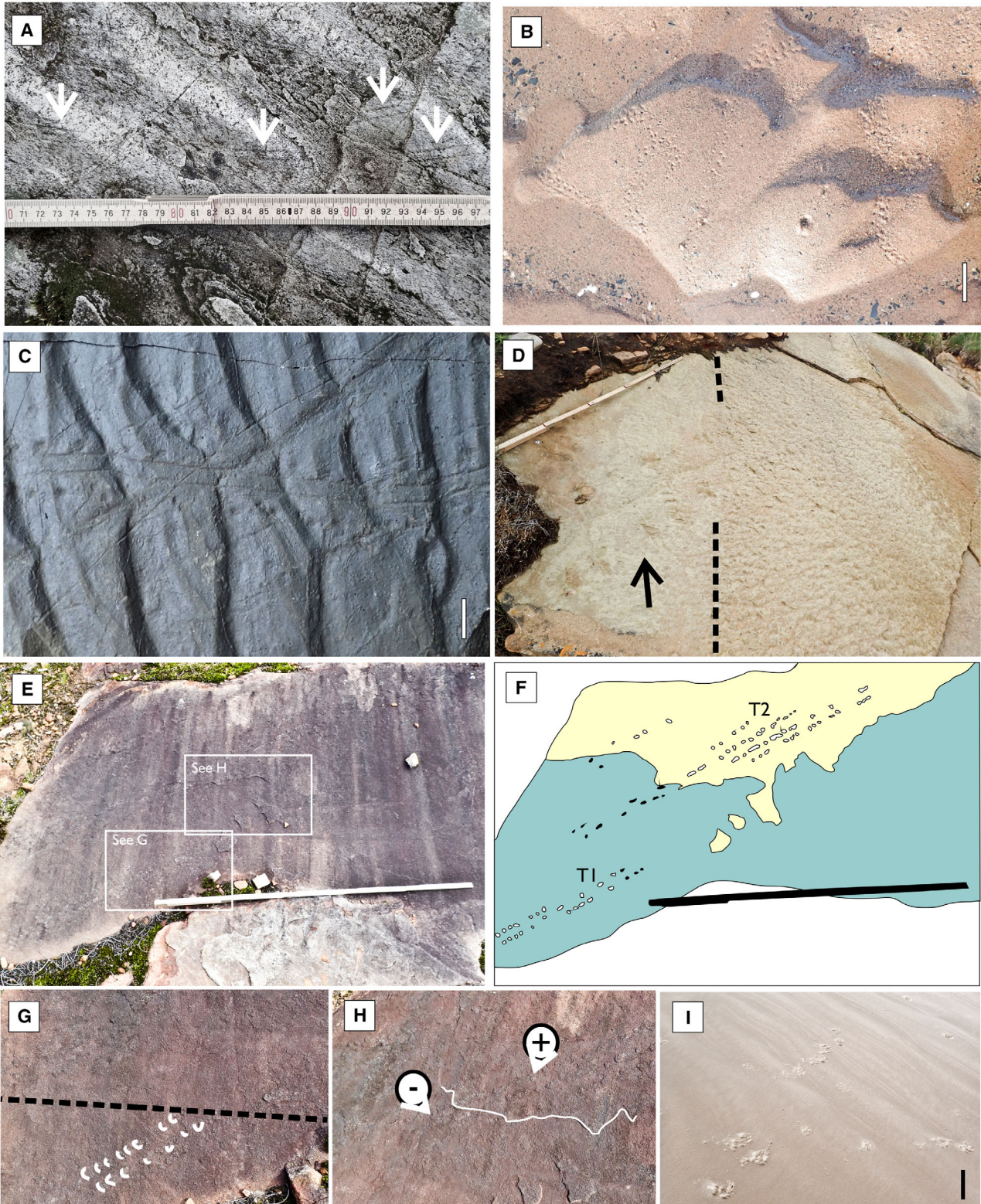
Table 2. (continued)

	Formative interval	Type	Frequency of occurrence	Time taken to form feature	Maximum persistence as true substrates	Evidence for true substrate
Fluid scour marks (flutes, gutters)	Relict E, or E + D	Singular	Common	1	3	When palimpsested with Category A forms
Channel cutbanks	Relict E, or E + D	Singular	Common	3	4	When palimpsested with Category A forms
<i>In situ</i> dropstones	S or D	Singular	Rare	1	4	When palimpsested with Category A forms
<i>Internal bed signatures which indicate a true substrate existed directly above, and will be present unless it has been removed by erosion</i>						
Infaunal burrows	S dominant	Pervasive	Very common	2	4	When upper contact with burrow openings preserved or surface with Category A forms
Plant root structures	S dominant	Pervasive	Common	3	4	When upper contact with standing fossil plant, VISS or surface with Category A forms
Palaeosol profiles	S dominant	Pervasive	Common	3	4	When upper contact with surface with Category A forms

Fig. 16. Examples of incorporating the concept of true substrates into palaeoecological studies. (A) Ripple-marked true substrate, with discontinuous arthropod trackways (arrowed) preserved only on ripple crests, Ordovician Borrowdale Volcanic Group, Lum Pot, Cumbria, England. (B) Modern analogue of (A), ripple marks with discontinuous arthropod trackways preserved only on ripple crests, as submerged sand in ripple troughs does not preserve track impressions. Rainy Cove, Nova Scotia, Canada (scale bar is 1 cm). (C) Arthropod trackway crossing over flat-topped ripples, as evidence for traverse of wind-reworked true substrate. Silurian Sundvollen Formation, Krok-sund, Norway (scale bar is 1 cm). (D) True substrate with a break in slope (highlighted), sloping gently downward to left of image and flat to right of image. Right side of the true substrate exhibits adhesion marks, testifying to wind-reworking, whilst left side of image shows tetrapod trackway (arrowed), apparently emerging from topographic low. Partial reworking of tetrapod trackway to adhesion marks on flat surface, suggests that left side of true substrate remained submerged, but that animal traversed both the submerged and emergent parts of the substrate. Devonian Gaza Formation, Tarbat Ness, Scotland (ruler is 1 m long). (E) to (I) Photographs and interpreted sketch of a bedding plane hosting parting lineation and arthropod trackways in the Silurian Major Mitchell Sandstone, Glenisla, Victoria, Australia (ruler is 1 m long). Close inspection reveals this to be a composite of two true substrates: an older surface (true substrate 1; green in F) with a partially preserved overlying veneer of a younger surface (true substrate 2; yellow in F). Two sets of trackways are visible (T1 and T2), with individual footprints either in positive epirelief (highlighted white in F) or as negative epirelief impressions (highlighted black in F). (G) Positive relief trackways (T1) obliquely terminate perpendicular to parting lineation (shown by dashed line), likely due to wave swash at a beach margin. (H) Positive relief tracks bear resemblance to tracks in modern emergent beach settings where compressed sand under animal footprints remains in place while surrounding sediment is deflated by the wind (see I: positive relief dog footprints on a modern beach, Alnmouth, Northumberland, England; scale bar is 10 cm). Although set T2 appears on both true substrates, its negative appearance on true substrate 1 must be as undertraces. Sequence of events leading to these amalgamated true substrates can be interpreted as follows: (i) deposition of true substrate 1, patterned with parting lineation by breaking waves; (ii) arthropods crawl obliquely up beach creating T1; (iii) tail-end of trackways reworked by breaking waves and resulting in sudden oblique termination (G); (iv) deflation of surface, leaving T1 in positive relief; (v) deposition of true substrate 2, patterned with parting lineation by breaking waves; (vi) arthropods crawl obliquely up beach creating T2, and palimpsesting undertraces onto true substrate 1; and (vii) wind deflation of true substrate 2, leaving T2 in positive relief.

(Figs 10B and 16K; Pemberton & Frey, 1984; Kotake, 1994; Davies *et al.*, 2009). Burrows have particular utility in vertical sections, for

distinguishing sampled from constructed topography (for example, Fig. 5C and E; Pollard *et al.*, 1993; Davies *et al.*, 2019).



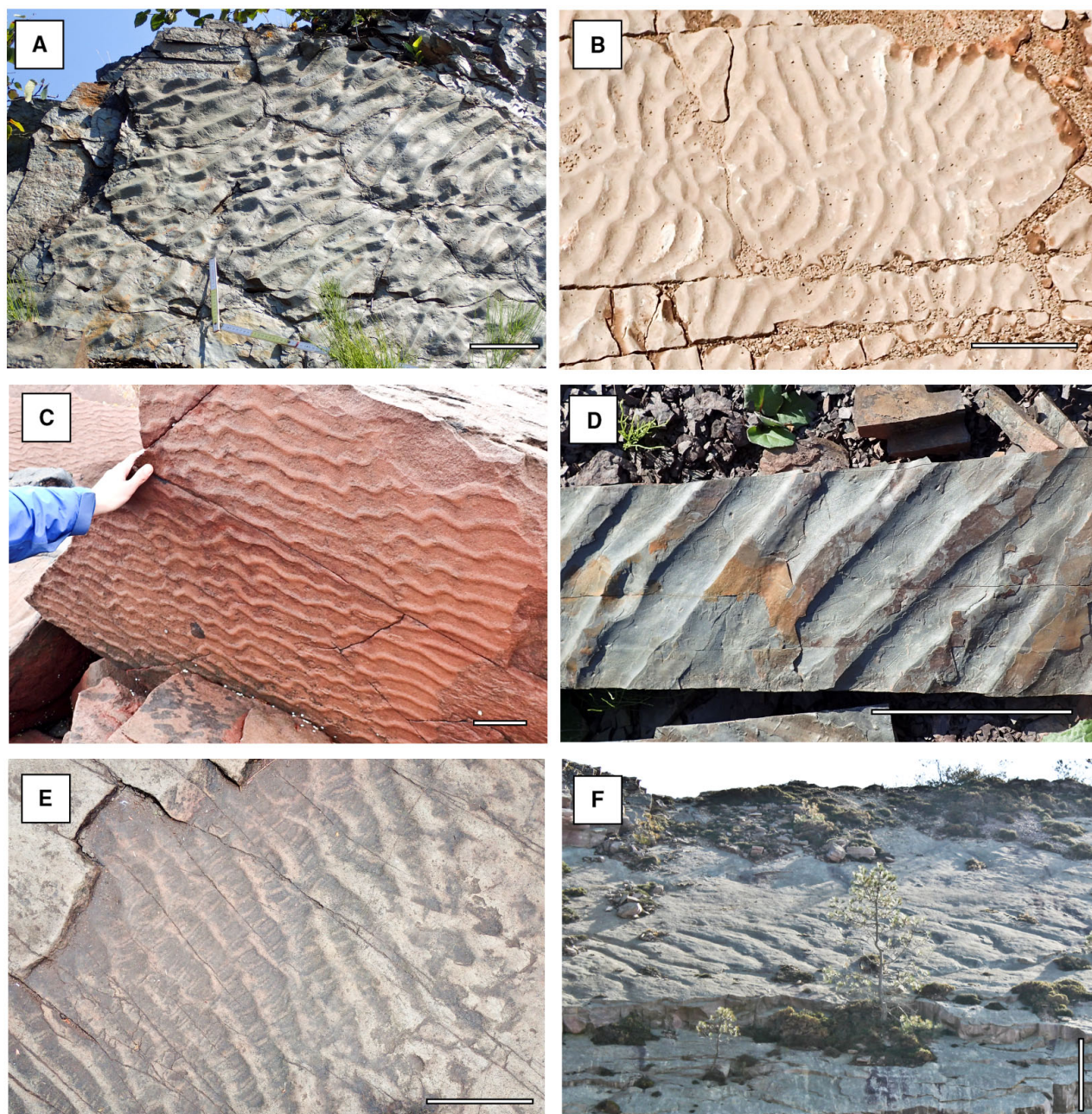


Fig. 17. Examples of true substrates providing evidence for hydrodynamic conditions during and after deposition. (A) Zigzag-shaped defects in ripple mark crests resulting from either a decrease in water depth or an increase in wave height or length (see Perron *et al.*, 2018). Mississippian Albert Formation, Bloomfield, New Brunswick, Canada. (B) Hourglass-shaped defects in ripple mark crests resulting from either an increase in water depth or a decrease in wave height or length (see Perron *et al.*, 2018). Cambrian Elk Mound Group, Wisconsin, USA. (C) Widely-spaced sediment starved ripples resulting from low sediment supply or migration across cohesive substrate. Neoproterozoic Diabaig Formation, Inverallican, Scotland. (D) Flat-topped ripples resulting from wind-shaving of exposed ripple crests on an emergent substrate. Mississippian Albert Formation, Bloomfield, New Brunswick, Canada. (E) Ladder ripples resulting from secondary ripples developing in ripple troughs during lowering of water level. Cambrian Potsdam Sandstone, Ausable Chasm, New York, USA. (F) Asymmetrical dunes preserved in full relief, indicating current flow in marine sands. Cambrian Erquy Formation, Port Barrier, Brittany, France. Scale bars 20 cm in (A) to (E), 2 m in (F).

Temporal significance of diagnostic features

True substrates record the top of a former surface active layer on which signatures can have been recycled during net stasis due to high frequency iterations of deposition and erosion. Thus, while many of the features listed in Table 2 form over relatively short timescales, they can have replaced antecedent signatures on the same ancient lithic surface [for example, multiple trains of ripple crests could traverse a patch of substrate, but only the last to do so before interment will be preserved (e.g. Myrow *et al.*, 2018)].

The bias towards late-stasis, high-frequency surficial signatures on true substrates means that other characteristics, often preserved as vertical profiles within a bed, can be required to permit an estimate of the full longevity of stasis. In alluvium, consideration of palaeosols can put an upper bound on stasis duration (e.g. Miall & Arush, 2001). In such facies, Demko *et al.* (2004) distinguished palaeosols that developed internally within floodplain lithologies from those that showed prolonged stasis over 10^3 to 10^6 years and bounded strata deposited in different palaeohydrological or climatic settings. A benefit of recognizing stasis duration from geochemical alteration is that it can permit the distinction between geochemical profiles or authigenic minerals generated by high frequency weather, versus low frequency climate.

In other settings, infaunal bioturbation can have value for estimating the duration of stasis (for example, estimated from the time taken to construct burrows: Gingras *et al.*, 2008; Davies *et al.*, 2019). Truncated vertical burrows, or biased preservation of deep tier trace fossils, can be used to infer stasis within stratal successions that are otherwise dominated by constructed surfaces (Goldring, 1964; Bromley & Ekdale, 1986; Frey & Goldring, 1992; De, 2002; Buatois *et al.*, 2015). The degree of overprinting of multiple generations of burrows can also be used to estimate the relative persistence of stasis (e.g. Wheatcroft, 1990; Bentley *et al.*, 2006; Gingras *et al.*, 2011; Savrda, 2014) with the caveat that bioturbation is rarely pervasive across the entire spatial extent of a depositional environment, so overprinting is not inevitable (Miller & Smail, 1997; Dashtgard, 2011; Marenco & Hagadorn, 2019).

The temporal persistence of an unchanging elevation of the lithic surface is dependent on the recurrence interval between deposition or erosion episodes and is thus environment-

dependent (Fig. 13). The dominant state of in-channel fluvial dunes is frequent reworking through deposition and erosion, yet some patches of an in-channel area will host abandoned dunes which exist in stasis and get preserved in the SSR as formsets (Reesink *et al.*, 2015). Likewise, patches of dynamic shallow marine sand-waves can remain in stasis for a year or more whilst the system remains generally in motion (Dijk & Kleinhans, 2005; Davies *et al.*, 2019). Beach and tidal flat surfaces can remain without disturbance for predictable ranges of hours to months, depending on position on tidal transect and storm surges (Kvale, 2012; Spencer *et al.*, 2015). In other settings, where agents of deposition and erosion are spatially or temporally concentrated in an environment, stasis can be prolonged: the recurrence interval of storms at specific sites on shallow marine shelves is consistently estimated at a few centuries (e.g. Thorne *et al.*, 1992; Kowalewski & Bambach, 2008; Hampson *et al.*, 2015), turbidite recurrence at a deep marine site can be up to thousands of years (Clare *et al.*, 2014), and the recurrence of deposition on fluvial floodplains occurs on timescales from years to millennia (Malamud *et al.*, 1996). The expected range of stasis durations recorded by true substrates should thus depend on the palaeoenvironmental facies in which they are hosted.

Identifying and interpreting D-E-S-D true substrates

Although simple D-S-D true substrates may be identified by just one of the sedimentary features noted in Table 2, D-E-S-D and other more complex true substrates require a suite of evidence to prove event separation (i.e. a stasis disconnect between E and D; Fig. 18; Goldring & Aigner, 1982; Davies & Shillito, 2018). Even though such crucial positive evidence is not guaranteed to be present in every instance, there is growing evidence that such surfaces are very common in the SSR.

Some D-E-S-D surfaces have long been recognized. For example, scour-and-fill structures in marine storm deposits reveal evidence for event separation when the erosional topography yields ichnological signatures of colonization or has acted as a sheltered trap for the accumulation of fossil debris (Goldring & Aigner, 1982). Likewise, Stokes surfaces in aeolian settings, which develop due to erosional deflation, but which are not immediately interred, are further

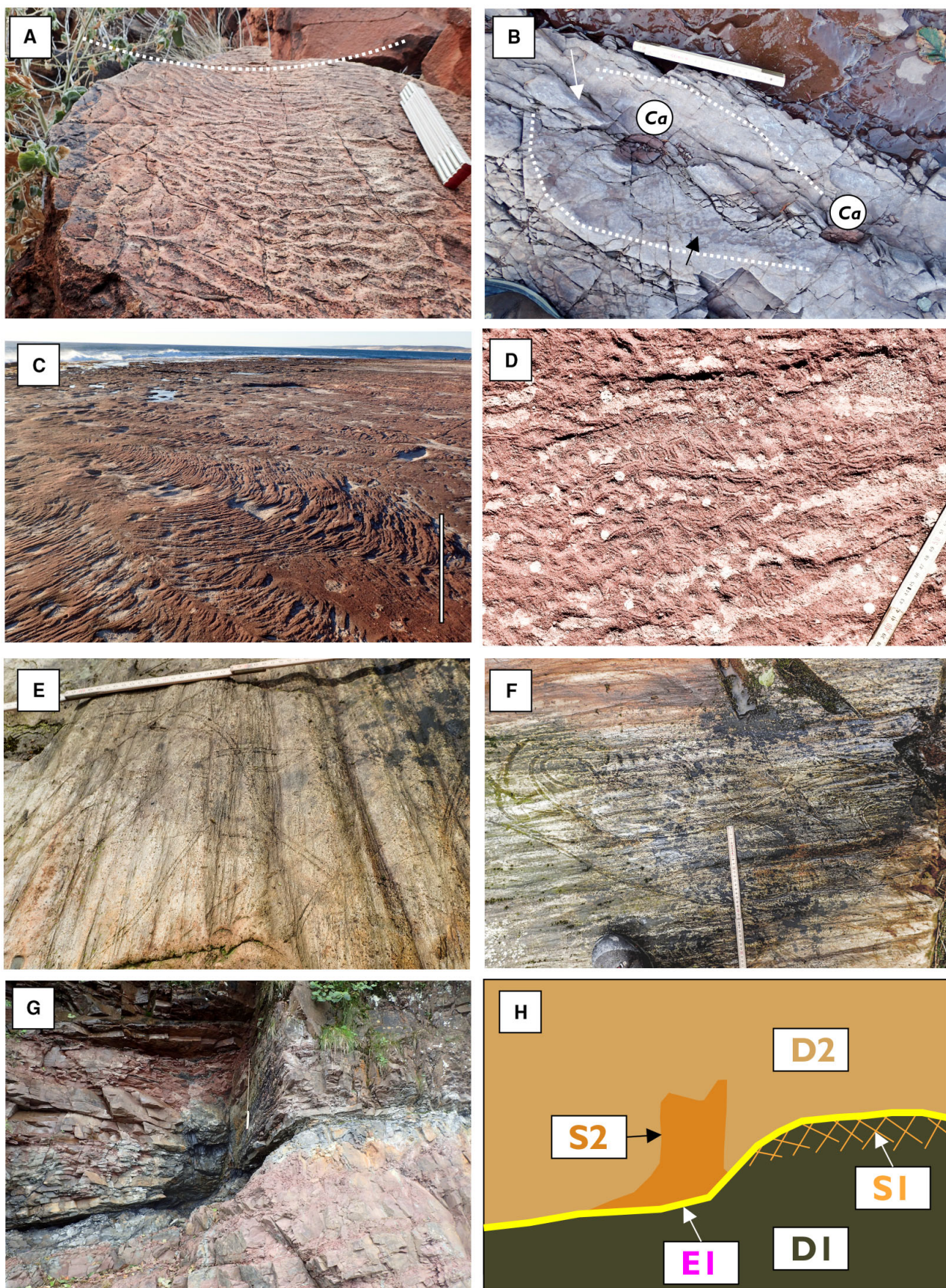


Fig. 18. Evidence for D–E–S–D true substrates. (A) Scoop-shaped puddle (topography highlighted), formed by erosion, has acted as a true substrate, revealed by the interference of ripples within the concave depression. Silurian Mereenie Sandstone, Watarrka, Northern Territory, Australia (ruler is 20 cm long). (B) Vegetation-induced sedimentary structure (*sensu* Rygel *et al.*, 2004) of a scoured hollow (white dashed lines) and mounded vegetation shadows (white arrow), formed due to erosive scour around the base of two standing *Calamites* plants (Ca). The scour persisted in stasis for an interval after its formation, as seen by the interference drip impressions (black arrow) formed by water dripping from the plants. Pennsylvanian Tynemouth Creek Formation, Gardner Creek, New Brunswick, Canada (ruler is 20 cm long). (C) and (D) Truncated estuarine dune foresets in the Silurian Tumblagooda Sandstone (Jake's Point, Western Australia) appear to be constructed topography, but closer inspection (D) reveals the truncated horizontal plane had been densely colonized by the gastropod tracemakers of the surficial trace fossil *Psammichnites* [see Davies & Shillito, 2018; scale bar in (C) is 1 m; visible part of ruler in (D) is 15 cm]. (E) and (F) Erosional groove marks in volcanoclastic tuffs that have stayed in stasis after their initial scour, as revealed by the superimposition of multiple arthropod trackways of both *Diplichnites* and *Diplopodichnus*. Late Ordovician Borrowdale Volcanic Group, Lum Pot, Cumbria, England [see Shillito & Davies, 2019b; visible part of ruler is 30 cm in (E) and 25 cm in (F)]. (G) and (H) Possible D–S–E–S–D substrate in the Pennsylvanian Tynemouth Creek Formation, McCoy Head, New Brunswick, Canada. Interpretation of sequence of events shown in (H) D–S–E–S–D true substrate is exposed only in small patches along yellow line, but vertical bedding contacts reveal history: first deposition interval D1 revealed by sediment pile (likely multiple D events, \pm E or S), followed by stasis interval of palaeosol development (S1), then erosional downcutting of a fluvial channel margin (E1), then further stasis, permitting the growth of a large cordaitalean tree on the channel margin surface (S2), before this is interred during a second interval of deposition (D2; measuring stick is 1 m long).

examples of D–E–S–D compound sedimentation states (Stokes, 1968; Fryberger *et al.*, 1988).

The potential abundance of D–E–S–D surfaces in deep-water successions has recently been highlighted by Peakall *et al.* (2020). They note instances from the erosive bases of Bouma sequences where: (i) a surface exhibiting flute marks in a proximal setting can exhibit tool marks in a distal setting, showing that flow energy diminished down dip such that it was no longer erosional, yet sufficient to continue transporting the largest calibre debris; and (ii) groove marks can be cut by debrites that bypass down dip, showing that they remained in stasis until later cast by turbidites. Peakall *et al.* (2020) thus demonstrate that, contrary to popular belief (e.g. Middleton & Hampton, 1973), many erosive sole structures record scour prior to an interval of stasis, and do not necessarily have a genetic link to the turbidite deposits that overlie them. Direct evidence for this scenario exists where graphoglyptid trace fossils (for example, *Paleodictyon*) can be seen superimposed on negative epirelief flute casts, indicating that they were registered in an interval of stasis after erosional fluting but before depositional casting (Monaco, 2008; Monaco & Checconi, 2010). Previous explanations for such phenomena have assumed that the traces were shallow-infaunal but that gently erosive turbidity currents partially exhumed them to just the right level before casting (Seilacher, 1977; Cummings & Hodgson, 2011). Such explanations inadequately account for why there is

such regularity of form in the traces across multiple instances, why they follow undulatory flute cuts, and do not reconcile with the fact that modern graphoglyptid traces are epifaunal constructions (Ekdale, 1980). Removing the unnecessary assumption that there is a genetic link between scour surface and overlying sediment offers a holistic explanation.

D–E–S–D true substrates have now been reported from many environmental facies including those of deep marine fans (Monaco, 2008; Monaco & Checconi, 2010; Peakall *et al.*, 2020), marine shelves (Goldring & Aigner, 1982), estuaries (Davies & Shillito, 2018; Fig. 18C and D) and aeolian settings (Stokes, 1968; Fryberger *et al.*, 1988). Figure 18 provides additional examples from alluvial and volcanoclastic facies. Taken together, it is clear that D–E–S–D true substrates and event separation are pan-environmental and may be extremely common, as would be predicted by accepting that stasis is the normal state in most sedimentation systems (Tipper, 2015). They are likely to be often under-determined because their positive diagnosis relies on the fortuitous observation of non-universal evidence (i.e. little is known about barren sedimentary surfaces, Dott, 1983; Paola *et al.*, 2018). However, as it is possible that they are no less common than D–E–D surfaces, it is advisable that any erosive surface encountered in the SSR is considered under-determined unless there is positive evidence for discriminating whether it is D–E–D or D–E–S–D.

PRESERVATION OF TRUE SUBSTRATES

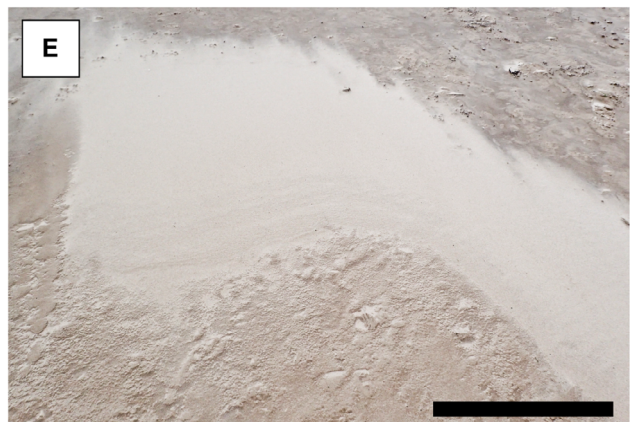
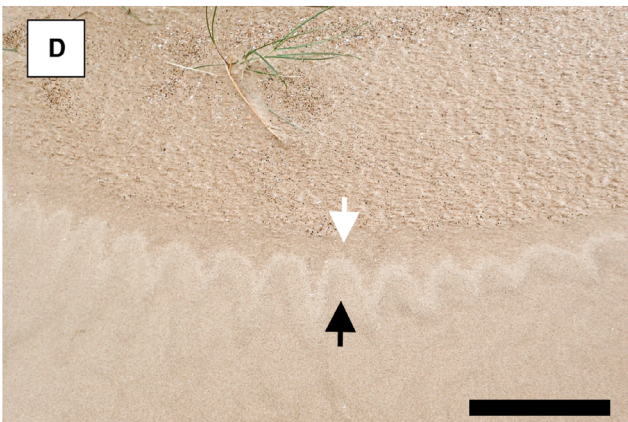
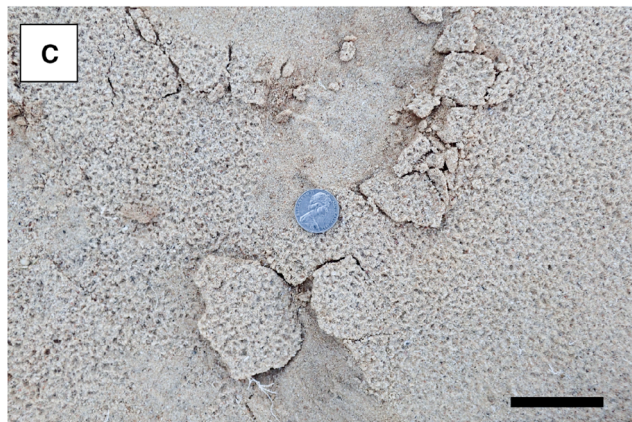
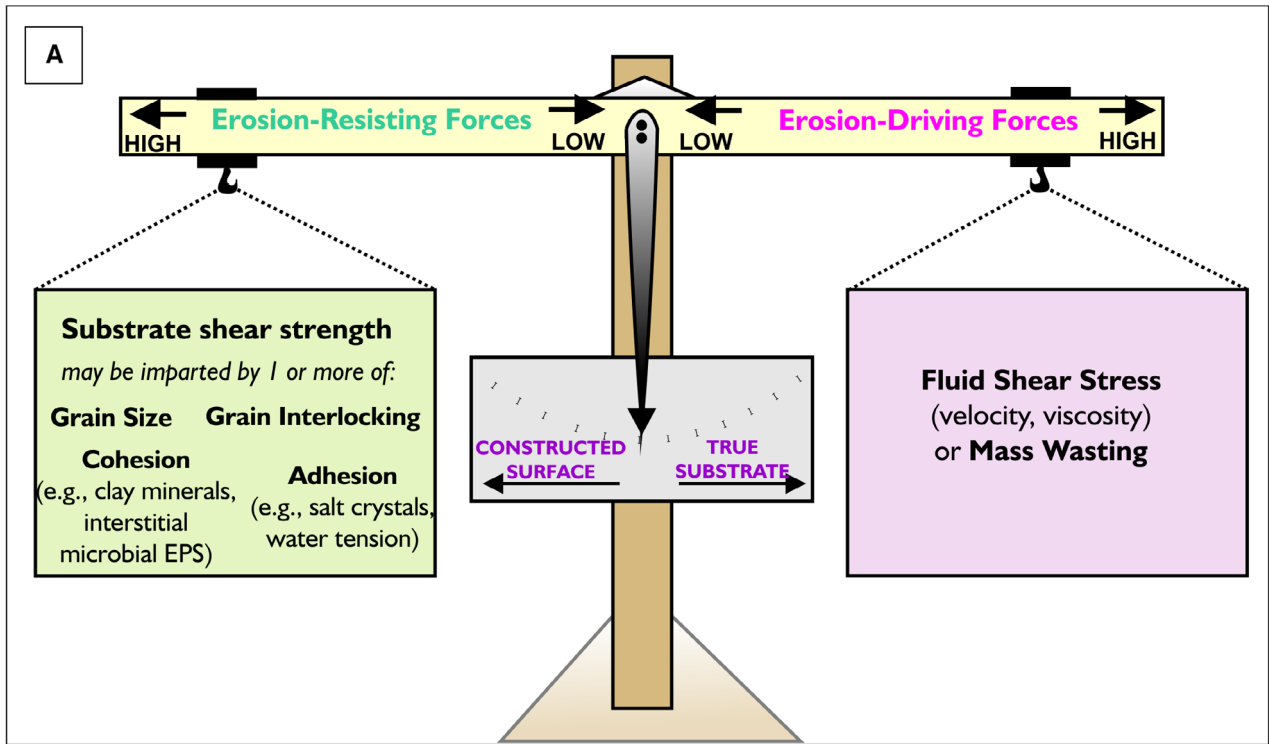
Miall (2015) noted that: “geologists have long asked questions like this: ‘Why is this particular crossbed set present in the geological record, out of all the multitude of similar deposits that must have been laid down?’”. Such questions are especially common when true substrates are encountered: the delicate and intuitively transient nature of many surficial features has frequently inspired special explanation. It has been said that: (i) arthropod trackways are only preserved in sand where biofilms were present (Seilacher, 2007, 2008); (ii) shallow scratch-mark trace fossils cannot be preserved without rapid burial, microbial mat-sealing or early diagenesis (Luo & Chen, 2014); (iii) substrates need to be hardened to preserve delicate structures (Moussa, 1974); (iv) thin sands that exhibit D–S–D without erosion were probably microbially-bound (Tarhan *et al.*, 2017; Retallack, 2019); and (v) that casts of soft-bodied organisms require microbial mats and episodic upper-flow regime or storm sedimentation to extend their preservation window (Gehling, 1999; Briggs, 2003; Hagadorn & Belt, 2008; Laflamme *et al.*, 2013). The recorded occurrence of some features has even been denied as an artefact of misidentification: ancient adhesion marks have been ascribed to microbial activity because those due to water tension ‘should’ be readily reworked (Porada & Bouougri, 2007a,b; Sarkar *et al.*, 2008, 2011; Petrov, 2015); raindrop impressions have been reinterpreted as gas bubbles because the former

‘should’ be ephemeral (Moussa, 1974); and wrinkle marks and multi-directed ripple marks have been considered more likely to be microbial in origin than occurring by abiotic loading on unbound substrates (Hagadorn & Bottjer, 1997; Eriksson *et al.*, 2010).

It is undoubtedly true that factors such as early substrate hardening, the presence of clay minerals, microbial binding, surface moisture and salt crusts can promote the preservation of surficial forms by enhancing substrate resistance to degradational forces (e.g. Davis *et al.*, 2007; Scott *et al.*, 2010). In some cases, it should not be unexpected that direct geological evidence for one or more of these playing a role in the preservation of a particular true substrate is found. However, it is here contended that they are not fundamentally prerequisite. The faithful preservation of surface features should be understood as dependent on a balance between erosion-resisting forces and erosion-driving forces where both are of equal importance (Fig. 19).

Within this conceptual framework, the preservation of surficial true substrate features is ultimately governed by burial preservation: event deposition preceded by little or no scour (Simpson, 1957; Hallam, 1975; Rindsberg *et al.*, 2005; Savrda, 2007; Ashton *et al.*, 2014). The scenario of rapid burial in a low energy environment may intuitively seem rare but must be achieved in any compound sedimentation state where stasis is directly followed by deposition (i.e. it applies to all true substrates). It arises because stasis is an innately ‘low energy’ state, and deposition is unavoidably rapid (approaching infinite) at the

Fig. 19. Factors promoting true substrate preservation. (A) Cartoon illustrating factors that promote the instantaneous preservation of true substrates at any specific cell within a sediment pile, where moving the position of either balance shifts the weight of the scales, and arrow points to resulting surface. (B) to (E) Examples of factors promoting, but not prerequisite for, true substrate preservation. (B) Biostabilization and cohesive sediment. Saltmarsh substrate exhibiting desiccation cracks, animal tracks and microbial-induced sedimentary structures at Alnmouth, Northumberland, England. Substrates such as these may resist erosion due to the cohesive properties of mud and microbial extracellular polymeric substances (EPS), while accessory properties of biostabilization [by both microphytobenthos and saltmarsh plants (here, *Spartina* and *Salicornia*)] include forcing sedimentation by settling of further mud, draping and interring existing substrates (e.g. see Brückner *et al.*, 2019; scale bar is 1 m). (C) Stabilization of granular sediment. Salt crusts can force adhesion of sand grains, providing additional shear strength, as seen in this instance of recent raindrop-marked sand which has retained the integrity of patterned fragments of the substrate despite being deliberately broken up. Murchison River, Western Australia (scale bar is 2 cm). (D) Insufficient shear stress to destroy true substrates during deposition of overlying sediment. Example showing how grain-avalanching from a small nebkha of wind-derived sand (white arrow, with wind adhesion marks) has previously buried a ripple-marked beach surface (black arrow), now momentarily re-exposed by the active deflation of the nebkha margins, observed during high winds. Holkham Beach, Norfolk, England (scale bar is 10 cm). (E) A combination of the above. This image shows an instance where dry sand has been blown over damp beach sand, passively draping a substrate patterned with tracks and adhesion marks. The insufficient shear stress applied by the wind, coupled with the shear strength provided by the adhesive effects of interstitial water mean that the surface textures are (at least momentarily) preserved. Bamburgh, Northumberland, England (scale bar is 30 cm).



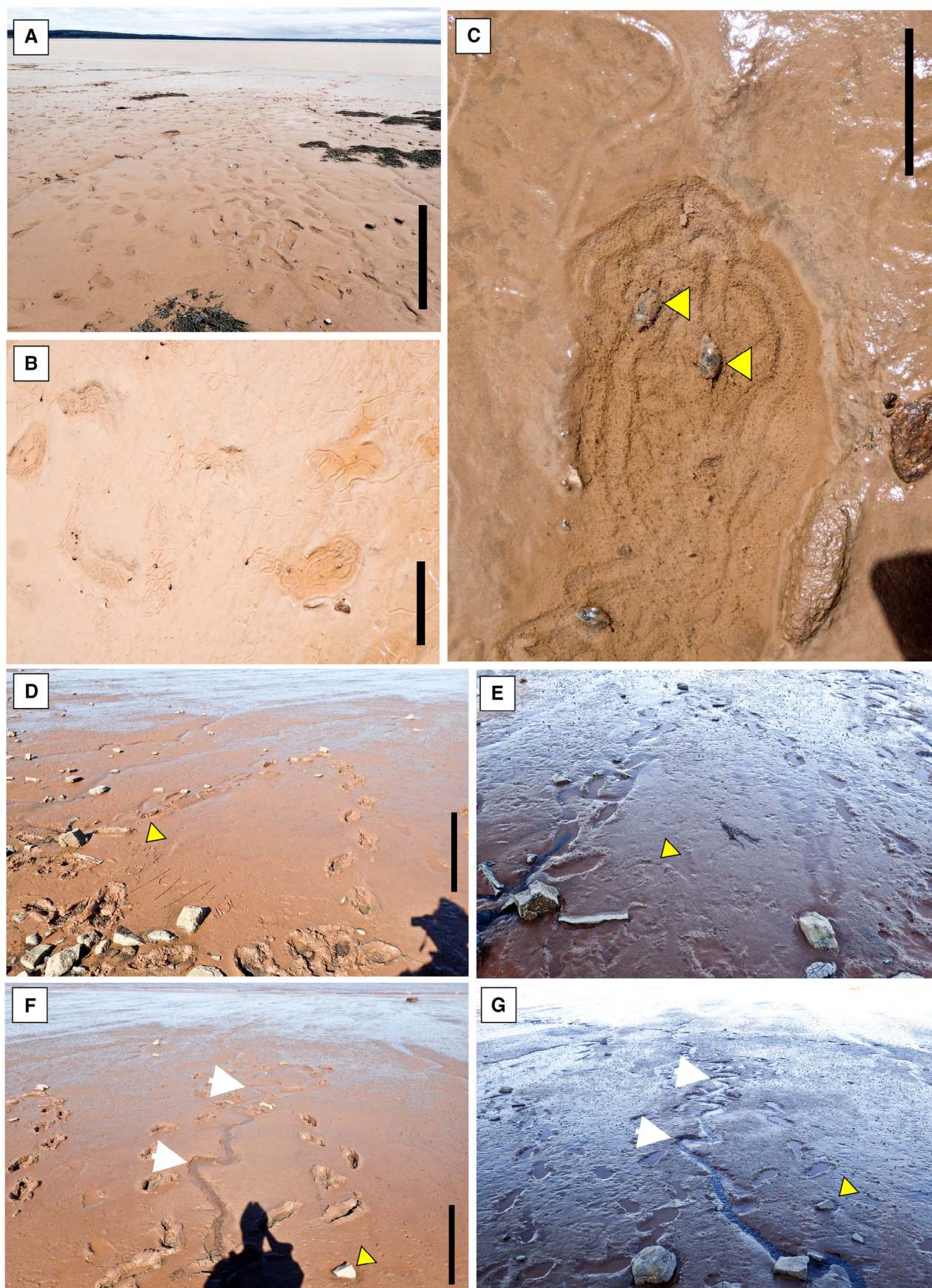


Fig. 20. Examples of short-term preservation of sedimentary structures on active substrates, from the intertidal zone of the Bay of Fundy, eastern Canada. (A) to (C) Modern human footprints on mudflats at Hopewell Rocks, New Brunswick, can be seen to have persisted since at least the previous high tide. These have acted as ponds for marine water during the ebb tide, into which gastropods have retreated (yellow arrows in C), producing dense concentrations of trails. (D) to (G) Modern human footprints made by the authors on intertidal mudflats at Horton Bluff, Nova Scotia, and revisited after 24 hours (i.e. two high tides). In (D), the date and time have also been lightly scratched in the sediment to a depth of approximately 3 mm ['SAT 8/9/18 1537' (yellow arrow)]. In (E), the form of the footprints remains, in addition to part of the scratched writing ('S', arrowed), the rest having been smoothed or buried. (F) and (G) show a natural small meandering drainage rivulet over the same interval, which has retained its form through both tidal highs (white arrows point to selected meander bends), despite the accrual of new mud, shown by the partial burial of the stone marked with the yellow arrow. Scale bar is 1 m in (A), (D) and (F), 20 cm in (B) and 10 cm in (C).

small spatial scale of a substrate of interest (e.g. Miall, 2015; Tipper, 2016; Straub *et al.*, 2020). Simple observations show it to be a truism that stasis is not *always* followed by erosion (Fig. 20), and so the inherent conditions for the preservation of true substrates should be expected to be met frequently in a wide variety of environmental settings. Stratigraphic modelling is also supportive of this contention, as recent advances (Ganti *et al.*, 2020) have shown that higher-order hierarchies of large bedforms can locally generate statistically large volumes of underfilled accommodation space, within which these conditions would be expected to be met frequently.

How does deposition follow stasis without erosion?

The specific mechanism for the preservation of a patch of true substrate arises because sedimentation states of S, E and D themselves have finite time and length scales. Accordingly, at any given instant there is spatial variation in S, E and D across the area of a sedimentation system (Reesink *et al.*, 2015), and whilst this remains true in the subsequent instant, the loci of S, E and D will shift spatially, and some of the patches in the sedimentation system will witness S followed by D, with no intervening E: instantaneously preserving some true substrates (Figs 21 and 22). This variance in the sedimentation states that create strata also means that contiguous stratigraphic-time is dismembered and smeared laterally: even low-accommodation settings may contain more complete records of stratigraphic time than would appear from a one-dimensional vertical section (Runkel *et al.*, 2008; Moody & Meade, 2014; Reesink *et al.*, 2015; Bhattacharya *et al.*, 2019; Davies *et al.*, 2019).

An appreciation of the spatial variance of strata-forming processes forcefully rebuts the

misconception that the erosional phase of a sedimentation event/episode must have been felt in the same place as the subsequent deposition (e.g. Seilacher, 2008). At small scales, at least somewhere within a sedimentation system, event separation between the deposition of two superimposed beds is inevitable (e.g. Goldring & Aigner, 1982; Davies & Shillito, 2018; Peakall *et al.*, 2020). The resultant faithful preservation of patches of true substrate are thus examples of the "strange ordinariness of the stratigraphic record" described by Paola *et al.* (2018) and also akin to what Gretener (1967) called the "rare event in geology". Gretener (1967) argued that remarkable geological events that seem improbable on human timescales (for example, major earthquakes) become probable when the temporal frame of reference is extended to that of the rock record. Many of Gretener's (1967) examples are now outdated, but the thesis holds true in this instance: few things seem more improbable than the preservation of a specific ripple mark on a beach, but the number of trial attempts to achieve this, even on just one patch of beach, is colossal.

Why do signatures of true substrates get destroyed?

If the preservation of true substrates is conceptually likely, it is pertinent to consider converse factors that lead to their destruction. There is a primary facies control on this, in that some parts of any environment are more likely to experience continuous deposition or frequent erosion (and an accordant dominance of depositional or constructed boundaries), such as within fluvial or estuarine channels (McMahon *et al.*, 2020; Muhlbauer *et al.*, 2020). However, even in those parts of environments where stasis dominates, signatures registered on substrates can diminish with prolonged exposure (e.g. Davies *et al.*, 2017), for several reasons.

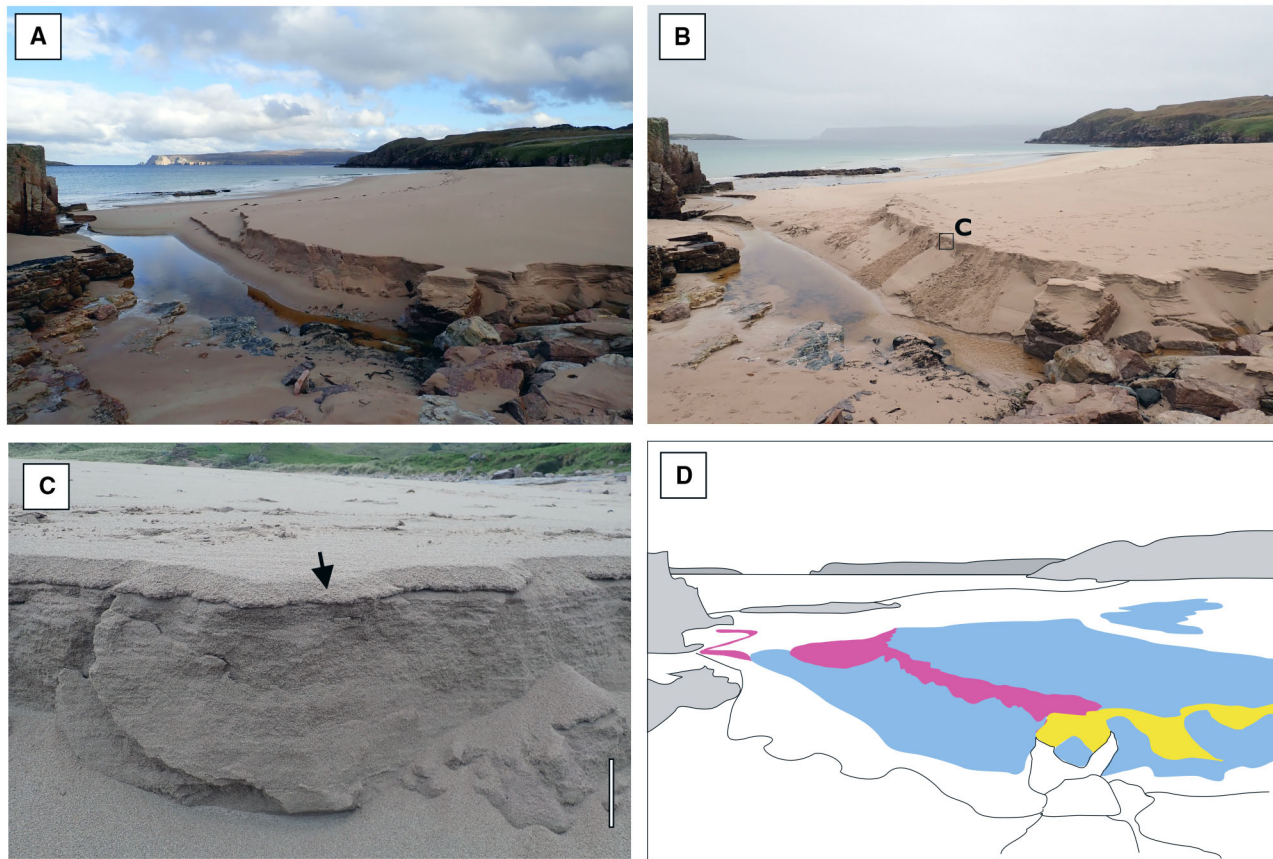


Fig. 21. Images of a beach (Sangobeg Bay, northern Scotland) taken two days apart, illustrating variability in the elevation of the lithic surface due to spatial and temporal variation in deposition, erosion and stasis. (A) Image taken at 15:45 on 28 September 2020. (B) Image taken at 15:45 on 30 September 2020, after the beach had been submerged by four high tides, including one high-tide storm event, since image in (A). Different parts of the beach experienced relative change to the lithic surface due to short-scale variation in D, E and S during these submergence episodes. (C) Close-up image of part of cut face in beach shown in (B), showing result of localized deposition state (arrowed) that deposited a layer of fresh sand, apparently without antecedent erosion (scale bar is 10 cm long). (D) Sketch of (B) showing patches of the wider lithic surface where beach level can be discerned to have been eroded (purple), deposited onto (blue) and remained unchanged in stasis (yellow), throughout the sedimentation state shifts that occurred between the stasis states shown in (A) and (B). Even in this area of volatile energy conditions and unconsolidated sand substrate, no one state has total spatial dominance.

Physical replacement

Jensen *et al.* (2005) suggested that surface trace fossils close to the sediment–water interface in sandy substrates have limited preservation potential due to rapid reworking by additional currents. This is true from the perspective of a specific trace fossil at the point of creation, but if a patch of substrate receives multiple visits from one or more trace-makers over its stasis interval, then traces imparted towards the end of that period can have as an equal a likelihood of preservation as any other late-stasis signatures.

Physical replacement during stasis can decrease the resolution of environmental signatures when

it involves overprinting rather than recycling or recurrence (for example, by multiple generations of burrows: Buatois & Mángano, 2013). In such instances, some palaeoenvironmental indicators may be lost at the expense of temporal information regarding the relative duration of stasis (see *Temporal significance of diagnostic features*).

Diffuse substrates

Diffuse subaqueous substrates have been argued to have limited potential for preserving surface features such as trace fossils (Jensen *et al.*, 2005). An animal trackway imparted into such sediment may begin to disappear almost instantaneously as

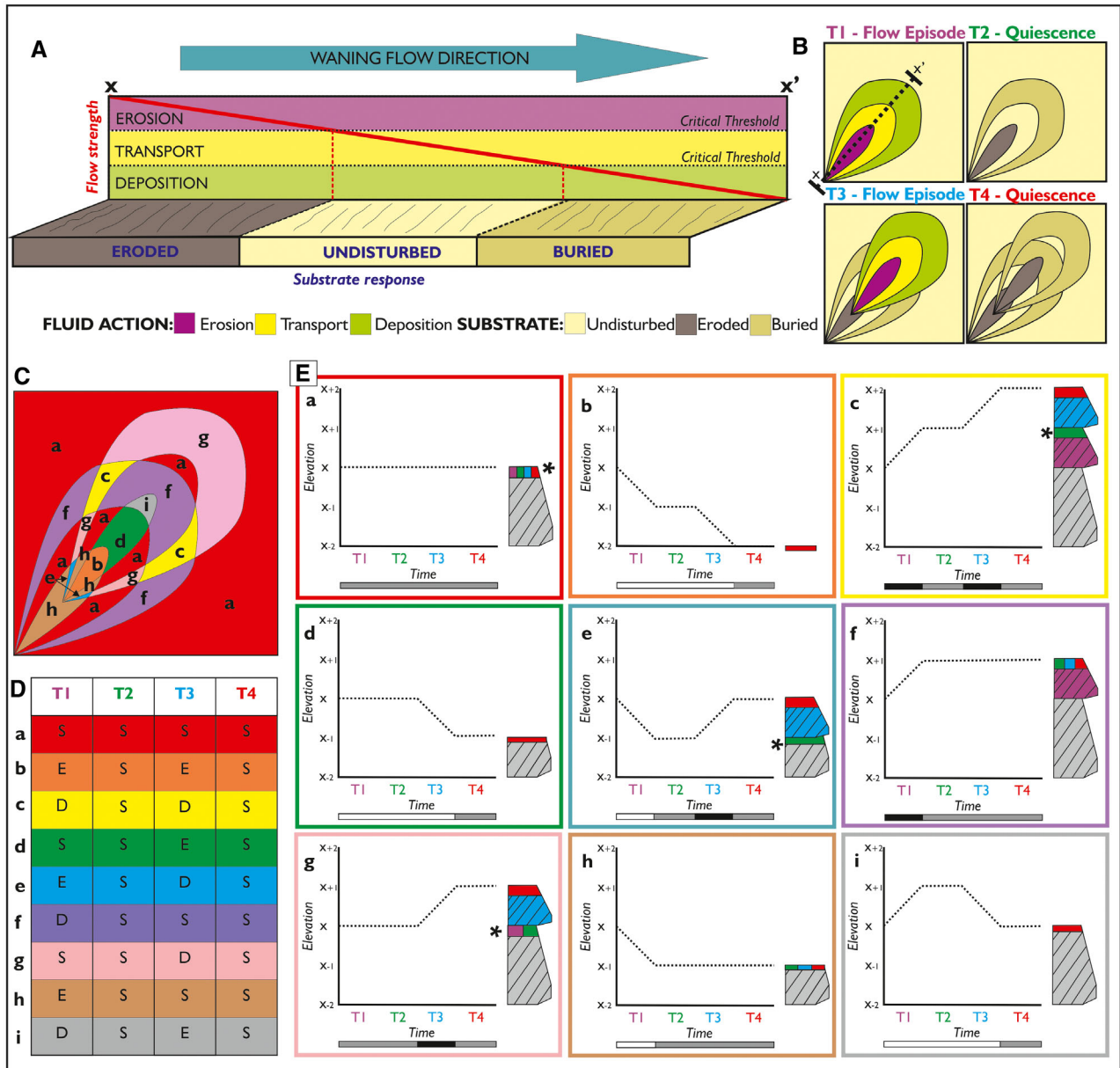


Fig. 22. Simplified conceptual model illustrating role of space and discordant successive flow events in preserving true substrates (modified after Davies & Shillito, 2018). (A) Waning flow diminishing through successive critical thresholds determines how a flow package interacts with a pre-existing substrate (shown as a rippled surface). (B) Plan-view of a waning flow event, dissipating radially and downstream within a confined, square area. The superimposition of two discrete events with different inception points (at time intervals T1 and T3), punctuated by intervals of quiescence and stasis (T2 and T4), results in spatially patchy averaged modification of the original (T0) substrate. (C) Sectors of plan-view area which, after two events, experienced one of nine ('a' to 'i') different historical combinations of deposition, erosion and stasis. (D) Succession of sedimentation states over time in the different areas. (E) Plots showing substrate elevation (y-axis) versus time (x-axis) and resultant lithostratigraphy and chronostratigraphy, for different spatial cells located within the sectors highlighted in (C). Alternative combinations of deposition (D), erosion (E) and stasis (S) result in variable preservation of time: either as sediment (black bar), potential post-depositional structures (grey bar) or missing due to erosion (white bar). Resultant stratigraphic logs show sediment accumulation as cross-bedded fining up beds and stasis surfaces as horizontal lines (colour-coded by time interval that they represent, with grey being pre-existing sediment from T0). True substrates that have developed and been interred between T1 and T4 are asterisked.

sediment grains resettle in the buoyant water after being disturbed by the registration of a footprint. If not interred immediately, the preservation of such surface features is thus unlikely. This does not negate the possibility that the synoptic topography could be preserved – if it were, the resulting bedding surface may be underdetermined as a true substrate.

In a particularly diffuse setting, such as a ‘soup-ground’ sea floor where a water-laden and incompetent fluid–mud mixture prevails and accrues only very slowly (e.g. Ekdale, 1985; Wells & Kemp, 1986), preservation of surface features may be negligible. However, in such instances, any resultant bedding surface would be more usefully considered to be a depositional bedding plane rather than a true substrate (as soupgrounds are effectively in a very slow state of D, rather than continual flux between D and S).

Decay

Fossil organisms can be informative components of true substrates, for example, organisms in growth position such as fossil trees (for example, Fig. 18G), or stranded soft-bodied organisms such as jellyfish (for example, Figs 2K, 10C and 10D; Kowalewski & Bambach, 2008). Yet such features face a greater array of preservational hurdles than abiotic forms because the physical degradation that occurs with extended time in stasis (Davies *et al.*, 2017) is exacerbated by biological decay.

Soft tissue can be physically broken down by scavengers and ambient attrition, and decay can continue even after burial, especially in porous and permeable sands with heightened oxygen flow (Sappenfield *et al.*, 2017). Yet while decay and recycling of biological material is often inevitable on, or within, a sedimentary substrate that is exposed to oxygen, there is no guarantee that every iterative decay process will be completed before a true substrate is interred. A single *in situ* organism could take time on the order of 10^{-1} to 10^2 years to decay to ‘nothing’ after death, but the time taken to remove it from the realm where decay is effective (for example, through burial) can be instantaneous. Because timescales of both decay and burial can be shorter than the range of true substrate longevity (Fig. 13), it is to be expected that some iterations of the decay process, initiated towards the end of an interval of stasis, will fail to complete.

The presupposed inevitability of decay has notably promoted special explanation for Ediacaran true substrates, where *in situ* casts of soft-bodied metazoans are not uncommon (Fig. 10F).

Suggested reasons for their preservation include microbial mats and episodic storm sedimentation extending the preservation window (Gehling, 1999; Briggs, 2003; Laflamme *et al.*, 2013), strong redox gradients in the absence of vertical bioturbation (Brasier *et al.*, 2011), early silicification (Tarhan *et al.*, 2016), or mineralization by microbial sulphides prior to the precipitation of silica cements (Liu *et al.*, 2019). The anactualistic nature of the Ediacaran oceans could favour these explanations, but Bobrovskiy *et al.* (2019) have proposed an alternative model that invokes differential sediment rheology in substratum and casting materials, explaining preservation without early cementation. If the presence of microbial mats and early cementation are not essential, then the preservation of Ediacaran fossil-bearing substrates should be no more unexpected than other true substrates in the rock record (for example, a simple ripple-marked bedding plane). This could potentially clarify why not all Ediacaran fossils occur with microbial mat evidence (Callow & Brasier, 2009), why surfaces with partially decayed Ediacaran fossils are known in addition to surfaces with no or well-preserved examples (Liu *et al.*, 2011), and why there are also sporadic records of ‘Ediacara type’ three-dimensional preservation throughout the Phanerozoic (for example, Fig. 10C; Brasier *et al.*, 2011).

A further instance of non-inevitable decay is provided by Miall (2015) and Holbrook & Miall (2020), who have rebutted claims that preserved standing fossil trees in Carboniferous strata required instantaneous seismogenic subsidence to bury them below the effective window of decay processes (Bailey, 2011). They note that the deposition of a volume of sediment necessary to inter a tree seems unlikely on timescales of human observation, but is actually just infrequent, and not uncommon on longer timescales of 10^2 to 10^3 years. If such deposition happens where there is sufficient underfilled accommodation space (for example, as is generated by higher-order hierarchical bedform elements in alluvial systems; Ganti *et al.*, 2020) deep burial of trees, insulating against decay, is to be expected on the timescales of stratal accumulation.

Over the whole duration of accrual of the SSR, decay must inevitably have diminished material biological signatures on true substrates to near negligible fractions of original populations. Yet equally, because the cessation of decay can be instantaneously instigated at the moment at which a true substrate is interred, on the scale of the whole SSR the preservation of

some casts of soft-bodied organisms or standing trees must be recognized as a simple and inevitable consequence of the way that sedimentary strata accrue.

OBSERVATION OF TRUE SUBSTRATES

Many of the signatures that can be observed on true substrates are recognizable because their contemporary equivalents form rapidly, well within the timescales of human experience. Why is it that these types of signatures, known to be transient at the present-day, dominate observations of true substrates? An explanation lies in the interplay between the time–length scale of ancient sedimentary processes and environments that have conspired to build the SSR, the natural hierarchy of sedimentary strata and the time–length scale recorded by present-day outcrops.

Time–length scales of SSR forming processes

Miall (2010, 2015) demonstrated how sediment packages could be grouped based on the timescale over which the processes that formed them operated [Sedimentation Rate Scale (SRS)]. They provided examples ranging from SRS1, operating over timescales of 1^{-6} years with an instantaneous sedimentation rate of 10^6 m ka^{-1} (for example, burst-sweep cycles depositing ripple laminae), to SRS12, operating over timescale of 10^7 years, where sedimentation rates could be as low as $10^{-3} \text{ m ka}^{-1}$ (for example, the filling of cratonic basins). Additionally, the shorter the timescale of the process, the more rapid the sedimentation rate (Miall, 2010, 2015). Significantly, the examples discussed also showed a general relationship with spatial scale – short timescale (low order SRS) sedimentary and geomorphic phenomena dominantly occur on short length scales, and long timescale (high order SRS) phenomena on long length scales (Kleinmans *et al.*, 2005; Davies *et al.*, 2020a; note there are a few exceptions to this, for example meteorite impacts). Additionally, these phenomena are hierarchical in nature (e.g. Ganti *et al.*, 2020; Holbrook & Miall, 2020): a ripple migrating up a stoss slope at SRS2 can contribute to the migration of an individual dune at SRS3; the migration of an individual dune at SRS3 can contribute to the development of an individual delta system at SRS8; and the development of an individual delta system at SRS8 can contribute to the filling of a basin at SRS10 to SRS12. In other words, many long time–length scale phenomena

innately incorporate nested iterations of successively shorter time–length scale phenomena.

The net result of this stratal hierarchy is that the accretion of the SSR favours the preservation of phenomena that occupy the shortest time–length scales as individuals, but which dominate the longest time–length scales as populations. An individual ripple mark at the point of formation has a negligible preservation potential, but as ripple marks have been constituents of higher-order phenomena, with a global distribution, for billions of years, the ultimate preservation of some has been inevitable, even though survivors are an infinitesimal fraction of original populations (Fig. 23). The same explanation can be extended to the preservation of true substrates, as fortuitously but inevitably surviving fragments of once larger-scale synoptic topographies.

Time–length scales of true substrates at outcrop

A further reason that high-frequency, small-dimension signatures are commonly observed on true substrates arises from the time–length scales recorded by samples of ancient sedimentary environments as rock outcrops. The spatial scale of rock outcrop is discretized by both finite limits of human effort/accessibility and the extent to which intensive contiguous stratal packages can be observed before termination [for example, at the outcrop margins; by cover of scree, vegetation or soil; or internally against joints, faults or major unconformities, (Allen, 1983; Marenco & Hagadorn, 2019; Shillito & Davies, 2019a; Davies *et al.*, 2020a)]. These finite vertical and lateral dimensions are compounded by a negligible depth scale because the observable outer skin of a geomorphological outcrop exposes only a two-dimensional slice through an original stratal pile (transected by recent erosion in a variety of vertical, horizontal and oblique aspects).

With this perspective, outcrop windows onto ancient basin fills are fragmentary and diminutive two-dimensional samples, within what was once a much larger and three-dimensional sediment pile. The amount of stratigraphic-time that they encapsulate is limited to that which passed between the instants of arrival of their earliest and latest constituent grains. The constituent palaeoenvironmental facies of an outcrop controls the specific scale of this interval, but it is never more than a fraction of that of the basin fill from which they were sampled. It can thus

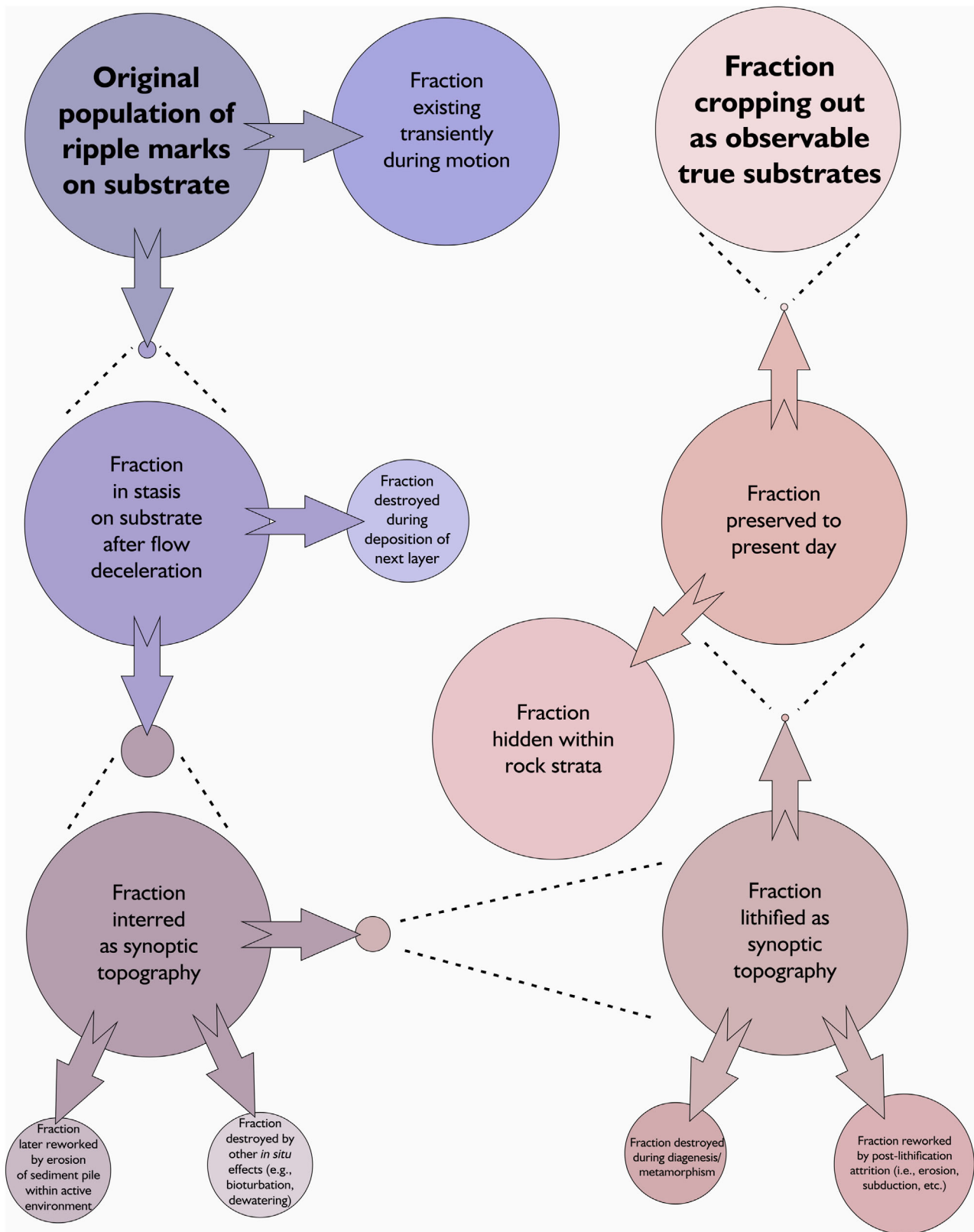


Fig. 23. Flow diagram showing how ripple marks observable on true substrates today are a negligible fraction of those that have existed on Earth in the past, and the pathways down which similar iterations have been lost. Size of circles is intended to represent approximate proportions relative to previous stage.

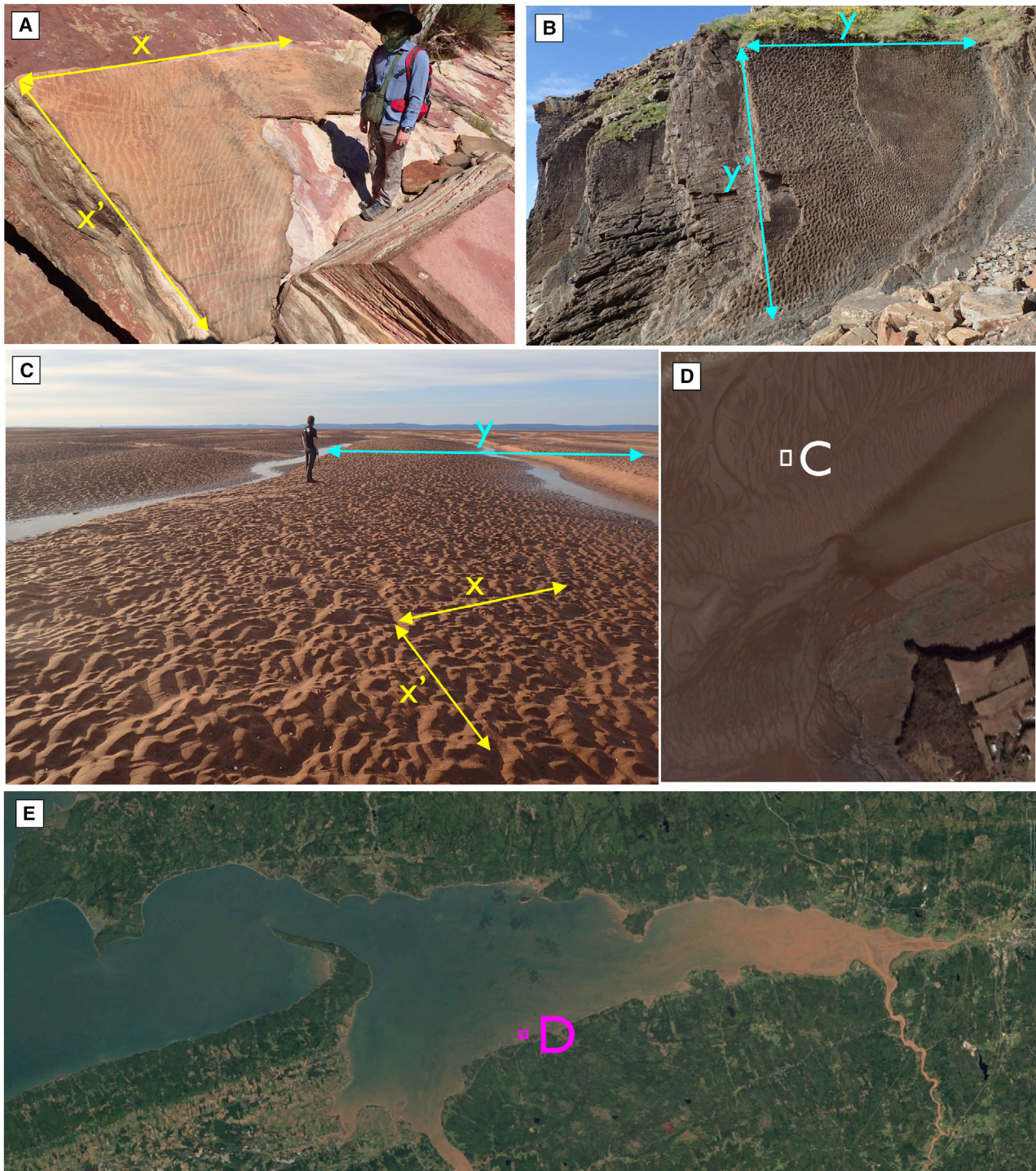


Fig. 24. Scale of accessible true substrates at outcrop relative to modern sedimentary substrates. (A) Typical-sized outcrop expression of a true substrate exhibiting ripple marks: blue lines x and x' are *ca* 2 m in length (Silurian Tumblagooda Sandstone, Kalbarri National Park, Western Australia). (B) Exceptionally-large true substrate exhibiting ripple marks: yellow lines y and y' are *ca* 12 m in length (Carboniferous Bude Formation, Bude, Cornwall, England). (C) to (E) Modern ripple-marked and dune-marked intertidal substrate at low tide in the Minas Basin of the Bay of Fundy (Nova Scotia, Canada). (C) Shows superimposed scales from (A) and (B); (D) shows approximate area visible in (C) and (E) shows approximate area visible in (D). Together these illustrate the negligible spatial coverage of even the largest ancient true substrates within the context of an active sedimentary environment. Satellite images in (D) and (E) are ©2020 Google and ©2020 Maxar Technologies.

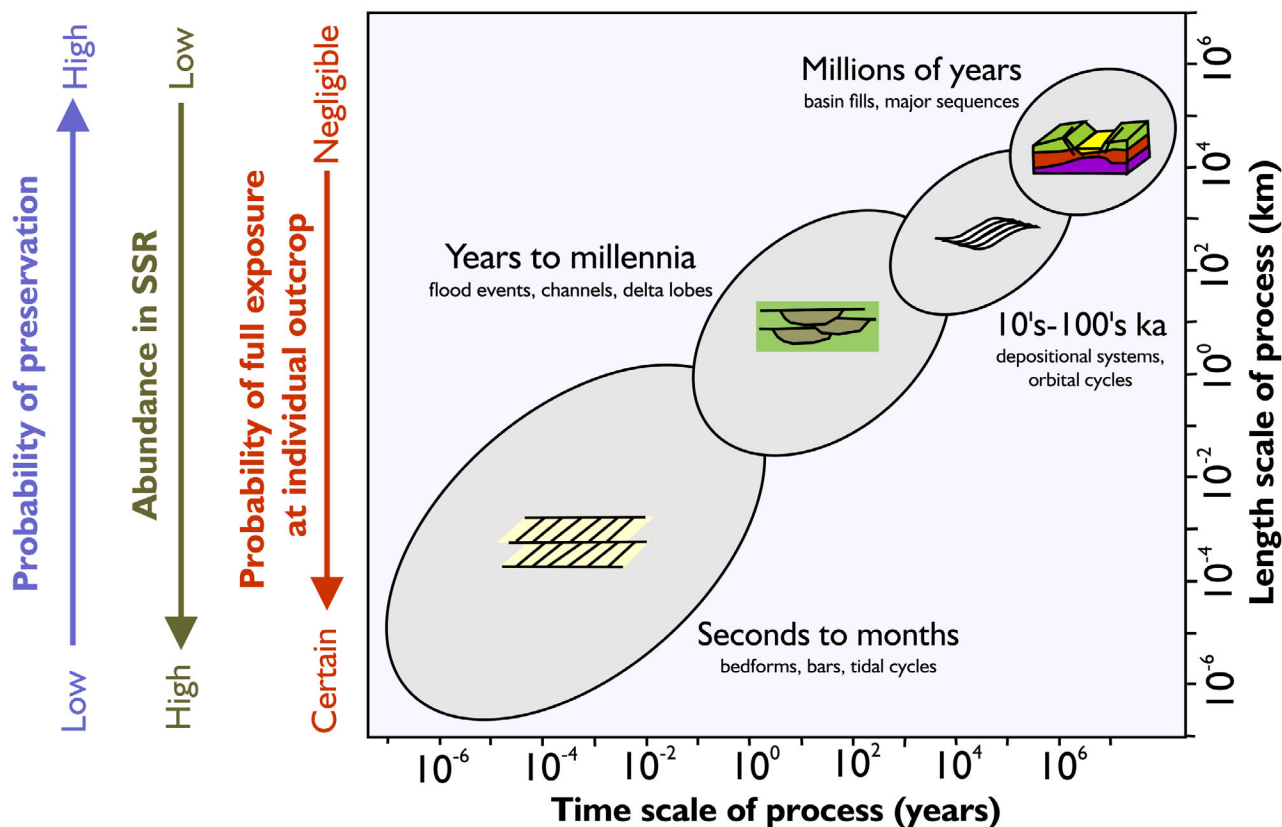


Fig. 25. Figure (modified after Miall, 2016b, fig. 11) showing correlation between time and length scale of some key deposit-forming and boundary-forming geological processes. As the stratigraphic record is hierarchical, low-frequency, large-scale signatures are an amalgam of multiple high-frequency, small-scale signatures. Thus, whilst, individually, signatures of high-frequency, small-scale processes have the lowest preservation potential at their point of inception (see also Fig. 23), they are more abundant in the rock record. Further, as they occur at spatial scales that are typically smaller than outcrops, they are more likely to be preserved at rock outcrop scale (and the presence of the smallest signatures is certain, by definition, if an accumulation of sediment is present).

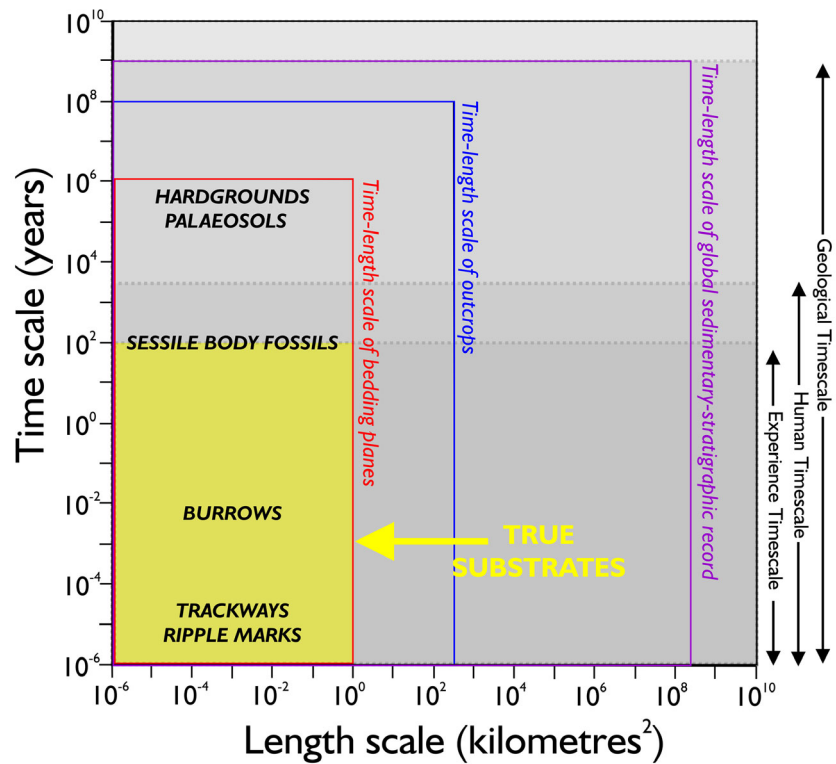
be expected that any individual sample is more likely to capture high-frequency stratigraphic breaks (for example, 10^{-6} to 10^3 years) than low-frequency stratigraphic breaks (for example, 10^4 to 10^7 years; Miall, 2016a,b), because of the far greater relative abundance of the former in the original sediment pile. Further, an outcrop can capture only a fragment of any constituent depositional element *within* an ancient environment, wherever the original dimensions of the element were more than those of the outcrop (Fig. 24; e.g. McMahon & Davies, 2018b). Accordingly, outcrops are biased towards completely archiving only the lower hierarchies of depositional elements and sedimentation rate scales (Ganti *et al.*, 2020; Holbrook & Miall, 2020; Fig. 25).

Ultimately, the discretization of spatial observations creates a discretization of temporal observations, and the inherently small scale of

outcrops biases observations of miniscule fractions of the total elapsed time in any sedimentary environment. In facies of a particularly energetic environment, it should not be unexpected that a small contiguous outcrop directly records as little as a few months of elapsed time, even if the temporal length of the stratigraphic unit that it partly composes is known to be many orders of magnitude longer (Davies *et al.*, 2019).

When further discretizing a spatial field of view to only a fraction of an outcrop, such as an individual bedding plane (e.g. Marenco & Hagadorn, 2019), there is an increasing likelihood of observing the shortest timescale geological phenomena that are endemic to whatever environmental facies is recorded (Fig. 24). At such minimal time-length scales, stasis is more likely to have prevailed than erosion (Straub &

Fig. 26. Time–length scale of true substrates relative to other geological phenomena. Annotations on the right of the image refer to hierarchical timescales: the geological timescale is the entire history of the Earth; within this is the timescale of human history and within this are timescales that an individual human observer may experience in a lifetime, and which are of short enough duration to witness the development and resulting forms from short timescale processes (for example, ripple mark formation). The length scale of true substrates is limited by outcrop geomorphology, but they also have a finite timescale, due to the fact that continued stasis leads to degradation and palimpsesting. True substrates are thus innately biased to recording phenomena that developed on timescales of analogous duration to individual observer experience.



Foreman, 2018). It is thus an inevitable result of the intersection between the time–length scale of outcrop and the time–length scale of hierarchical depositional elements that true substrates host signatures formed rapidly during stasis (Fig. 26).

True substrate abundance through geological history

Regardless of their actual abundance within a stratal pile, true substrates need to be accessible at outcrop to be interrogated. The specific geomorphology of an individual outcrop governs how many bedding planes can be accessed (for example, a stepped canyon versus a sheer vertical cliff face; Fig. 27; Shillito & Davies, 2020, 2021), which in turn partly determines how representative a sample of true substrates is returned. The total frequency of true substrates across the global SSR is further governed by other lithological characteristics. Unconsolidated sediments rarely split along bedding plane surfaces (for example, Fig. 6J; Savrda, 2007), which instead act as shear planes for failure within loose sediment (Barton, 1977). Such strata tend to be more common in Cenozoic successions, and so the global abundance of identifiable true substrates may be expected to diminish in younger strata.

Conversely, intensive diagenetic induration can strengthen bedding surfaces against failure and exploitation by weathering, reducing the number of bedding planes and true substrates accessible in outcrops of strata that have experienced low grade metamorphism. Such conditions are more likely to have been met in successions that have survived longer durations of time, and so there may also be a reduction in true substrate abundance in the very oldest strata. Finally, the number of true substrates that are accessible in an outcrop will generally increase if strata are tilted (Fig. 27), favouring abundance within older successions that are more likely to have experienced one or more orogenic events.

Together, these factors indicate that the intensity of true substrate sampling that is possible is not consistent throughout geological history, and so caution must be exercised when comparing trends in ‘average’ characteristics from different stratigraphic intervals. It may be that gross abundance of true substrates globally peaks in the Palaeozoic or Mesozoic, irrespective of fluctuations in global sediment volume (e.g. Peters & Husson, 2017). A bias may also have been imparted by the evolution of bioturbation, as the amount of sediment convection (and thus opportunities for true substrate reworking) intensified through the Phanerozoic (Thayer,

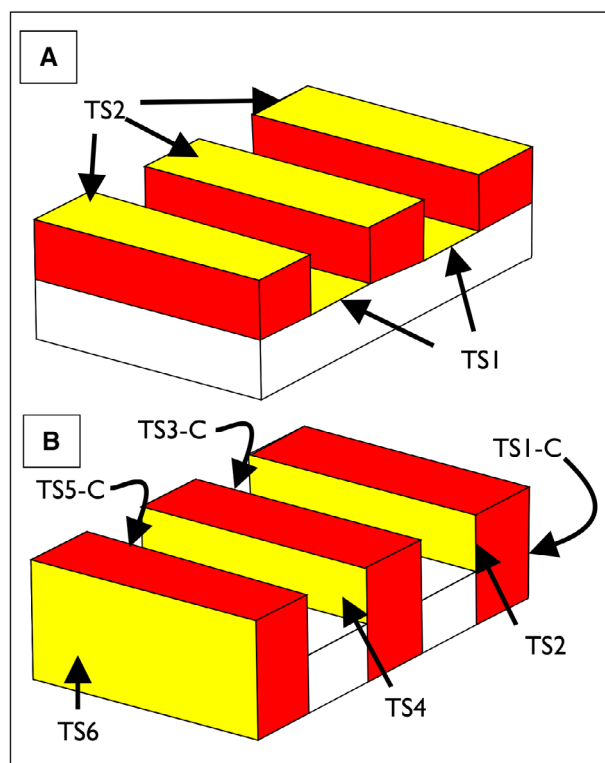


Fig. 27. Cartoon showing how interaction of bedding dip and outcrop geomorphology determines extent and number of potentially observable true substrates. Figure illustrates interbedded red and white beds that preserve true substrates (highlighted yellow) at every bed junction, both preserved within a castellated rock outcrop. (A) Horizontal bedding (younging upward) reveals only two true substrates (TS1 and TS2), but over a wide area. (B) Vertical bedding (younging towards viewer) reveals six discrete true substrates over a smaller area, three of which are preserved as casts on the bases of overlying beds (i.e. TS1-C, TS3-C and TS5-C).

1983). Certain true substrate features such as arthropod trackways (Seilacher, 2008) and flute casts (Tarhan, 2018) have been suggested to peak and then decline in abundance during the Palaeozoic, with destruction by bioturbation suggested to be the cause (although lithological and observation bias to global true substrate abundance offers an alternative explanation).

IMPLICATIONS

As individual true substrates are innately small in their time-length scale, it is important to ask if they are 'process complete' as windows on the past, in other words, whether these tiny slivers of recorded stratigraphic time are representative

of the broad spectrum of events from which they were sampled (Paola *et al.*, 2018). Paola *et al.* (2018) noted that any assessment of process completeness is partially qualitative, but the recurrence of signatures on true substrates can be informative. For example, the presence of ripple marks in multiple facies across every interval of geological history suggests that such features are extremely common. For this reason, on a local scale, the limited potential for stratigraphic correlation between disconnected true substrates can be beneficial, essentially providing the observer with a randomized sample. Consider an example of a single sedimentary unit of 1 Ma duration, disconnected fragments of which are exposed in scattered outcrops over a wide area. If the outcrops yield multiple instances of true substrates bearing arthropod trackways, then the random sampling of stratigraphically unanchored bedding planes means it is safe to imply that arthropod activity was very common in the depositional environment (cf. Davies *et al.*, 2019). By extension, if multiple instances of arthropod trackway-bearing true substrates are preserved in multiple different outcrops of multiple different formations of the same age but are absent in an equivalent sample of strata of a slightly older age, then an explanation must be sought. As the mechanics of stratal accrual are unlikely to have changed with time, a plausible explanation would be that these groups of strata cross the interval of time in which arthropods that had the capacity to impart trackways evolved. This hypothetical example illustrates that a very short time-length scale true substrate in isolation cannot reveal generalities, but the replication of similar signals in multiple random samples can. In other words, incomplete sequences with gaps should not be viewed as flawed records of processes, but rather faithful, literal records of separate processes (cf. Schindel, 1982).

True substrates are effectively grains of completeness in an incomplete record. Regardless of the antiquity of their host strata, they provide robust windows onto Earth surface processes that typically operated on timescales up to $ca 10^2$ to 10^3 years. In contrast, longer term geological processes usually require correlation between multiple outcrops, and so there can be a geological blindspot at the meso-scale because stratigraphic precision is rarely sufficient beyond 10^4 to 10^7 years (e.g. Schindel, 1980; Torrens, 2002; Erwin, 2006; Holbrook & Bhattacharya, 2012; Saraswati, 2019). However, the acknowledgement of

the time significance of true substrates means this blindspot does not encapsulate all processes on shorter timescales than 10^4 to 10^7 years, but rather only those processes between 10^2 to 10^3 years and 10^4 to 10^7 years. In this way, true substrates add an important caveat to the claim that "the stratigraphic record is largely unrepresentative of the geological past" (Amorosi *et al.*, 2020). They attest that, whatever the limitations and hurdles are for ascertaining rates and signatures of long-term allogenic changes, the geological record yields a remarkably detailed and accurate record of day to day processes (Paola *et al.*, 2018; Holbrook & Miall, 2020). As, by definition, they are intensive properties of *preserved* strata, they are also immune to issues arising from fluctuation in the extensive volume of the sedimentary record through history (Ronov *et al.*, 1980; Peters & Husson, 2017; Husson & Peters, 2018; Davies & McMahon, 2021). There may well be fewer Neoproterozoic true substrates than there are Carboniferous ones, but the veracity of a singular Neoproterozoic true substrate, once recognized, is no different to that of a Carboniferous one, nor a patch of substrate on present-day Earth: all of these can legitimately be directly compared and explanations sought for any differences.

The value of true substrates within the stratigraphic 'tattered manuscript'

The ultimate value of true substrates changes depending on the purpose of a geological investigation, which can be alluded to with Darwin's (1859) commonly cited analogy of the stratigraphic record as a tattered manuscript, in which only select sentences from scattered pages and chapters are decipherable (e.g. Schumm, 1998; Husson & Peters, 2018). True substrates are sentences that happen to be perfectly legible: their importance changes depending on what the reader wants the book to be. Treating the rock record as a novel, in which the history of Earth is desired to be read as a fluid narrative, then the sentences can have limited value because they are isolated fragments and often out of order. In this instance only generalities can be grasped at – the absence of a characteristic (for example, trace fossils) in the first few chapters of the book, and persistence following their first appearance, suggests something about evolution. Alternatively, if the rock record is being read as a collection of short stories, then the sentences can have more meaning from the standpoint of understanding

episodes of Earth evolution: the fragments from the story about Cretaceous non-marine substrates contain different characters than that about Cambrian ones. Finally, if the tattered record is read as a telephone directory, the value of true substrates shifts again. Just as a single tatter consisting of a name and number could retain all the inherent value that it ever held, so too can a true substrate from a particular place and instant of geological history. In this final sense, the total veracity of true substrates might be argued to have niche scientific value. Yet, as eerily familiar snapshots from deep history, they cannot but ground an observer's understanding of their own personal time and place on a long-lived and restless planet.

CONCLUSIONS

This paper presents a re-examination of true substrates; those bedding planes that faithfully record sedimentary phenomena that were registered at the ancient lithic surface. The paper shows that these are one common type of bedding surface generated within real-world sedimentation systems that are naturally in flux between deposition, erosion and stasis. Focussed identification of these features in future field investigations promises to improve cognition of the sedimentary–stratigraphic record as a historic chronicle, because true substrates can shed light on both stratigraphic time and the role of stasis in the construction of the record. Understanding that true substrate preservation is a fortuitous but inevitable by-product of stratigraphic accrual negates the need to invoke special taphonomic conditions for surficial phenomena, including 'exceptionally preserved' soft-bodied fossils. This perspective gives confidence that the sedimentary record harbours many snapshots of ancient 'alternative Earths', which can be literally read as archives of physical and biological surface processes operating on familiar, short timescales.

ACKNOWLEDGEMENTS

We would like to thank Ivan Martini and Kyle Straub for their reviews, Associate Editor Eric Hiatt and Chief Editor Peir Pufahl for their handling of this manuscript. APS was supported by the Natural Environment Research Council (grant number NE/L002507/1).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Manuscript received 19 November 2020; revision accepted 25 April 2021